On Selection of Optimum Diesel/Biodiesel Blend for CI Engine Using PROMETHEE/TOPSIS Method

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On Selection of Optimum Diesel/Biodiesel Blend for CI Engine Using PROMETHEE/TOPSIS Method

Major Project Report

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(Thermal Engineering)

By

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Declaration

This is to certify that

1. The thesis comprises my original work towards the degree of Master of Technology in Thermal Engineering at Nirma University and has not been submitted elsewhere for a degree of diploma.
2. Due acknowledgment has been made in the text to all other material used.

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Undertaking for Originality of the Work

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This is to certify that the Major project report entitled "**On Selection of Optimum Diesel/Biodiesel Blend for CI Engine Using PROMETHEE/TOPSIS Method**" submitted by Mr. Yogesh Prajapati (16MMET19), towards the partial fulfillment of the requirements for the award of Degree of Master of Technology in Mechanical Engineering (Thermal Engineering) of Institute of Technology, Nirma University, Ahmedabad is the record of work carried out by him under our supervision and guidance. In our opinion, the submitted work has reached a level required for being accepted for examination. The result embodied in this major project, to the best of our knowledge, has not been submitted to any other University or Institution for award of any degree.

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Abstract

From the birth of humans on this planet, energy becomes the crucial requirement for their continuous growth. Most of their energy demand is satisfied by fossil fuel resources. Due to improper extraction and use of excess fossil fuels, the environmental pollution is significantly increased. Uncertainties of fossil fuels, raising of petroleum prices, increasing demand of petrol and diesel, enhancement of environmental pollution, government's strict protocols and regulations forces the researchers to search for the alternative fuel, which should be economic, adequately available, energy conserved and environment friendly. Biodiesels are the monoalkyl fatty acid methyl esters that obtained from plant oils or animal fats through transesterification process. Biodiesels are the main research topic for alternative fuel of CI engine due to its renewability, vast availability and ability to reduce emissions. As most of the properties of biodiesels are comparable with diesel, it has the ability to substitute diesel fuel up to 20%. It is proved that up to certain percentage in the blend, the biodiesel improves the engine performance, reduces exhaust emissions and also causes less wear to the engine components. As farming and the agriculture are the main components of India's GDP, there is the significant opportunity of using biodiesels to reduce the foreign burden of petroleum fuels. Aim of most of the recent researches is to improve the use of plant oils based biodiesels in the CI engine. For diesel, we have one resource that is crude oil, while for the biodiesels, there are variety of edible and non-edible oils. This creates the confusion to end user that which biodiesel is best for use in CI engine. So, it is necessary to find out which plant oil based biodiesel is best for engine performance, combustion and emission. Since most of the research is related to the use of single or two separate biodiesel blends in CI engine, our aim is to find out the optimum percentage of two best biodiesels in a single blend with diesel at which the BTE, BP and net heat release are maximum, whereas BSFC, HC, CO, CO_2, NO_x and smoke emissions are minimum.

The study is carried out on the single cylinder, four-stroke, water cooled, direct injection diesel engine. We are selecting the eight different biodiesels based on the literature and availability of them nearby city area. Using full factorial method, first we have formed the 28 different biodiesel blends, in which each biodiesel blend consists of 25-25% of any two biodiesels and 50% of diesel. The experiments are performed at constant operating conditions of compression ratio, injection pressure and the injection timing. The reading are taken three times to increase the confidence interval. BSFC, BTHE, Peak pressure, Ignition delay, NO_x, HC and smoke density are selected as the base parameters for selecting the best two biodiesels and their optimum percentage. More weightage is given to emission parameters. Topsis and Promethee methods are used to assign the ranks to the results of first phase- 28 experiments and spearman's rank correlation coefficient is used to find the relative closeness of the ranks given by these two methods. Castor-Jatropha biodiesels are found as best two biodiesels according to the ranks of Topsis and Promethee methods.

In the second phase of experiments, the percentage of two biodiesel is reduced from 50% to 30%, while the percentage of diesel is increased from 50% to 70%. Five different Castor-Jatropha blends are identified having percentage of Castor-Jatropha as 25%-5%, 20%-10%, 15%-15%, 10%-20% and 5%-25%. Total six experiments are conducted using these five different Castor-Jatropha blends and pure diesel. Weightage and the selection of attributes are as same as done in first phase of experiments. Topsis and Promethee methods are also used to assign the ranks to the results of second phase- 6 experiments and spearman's rank correlation coefficient is used to find the relative closeness of the ranks given by these two methods. The biodiesel blend having 25% Castor, 5% Jatropha and 70% diesel is found as a optimum blend in terms of engine performance, combustion and emission.

Key words: Biodiesel, CI engine, Performance, Combustion and Emission analysis, First phase and second phase of experiments, Topsis, Promethee method, Castor-Jatropha.

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Nomenclature

$\lvert d_i \rvert$	Deviation
n	Number of repetitions of experiment
m	Target value of response variable
P_r	Reference pressure
S	Standard deviation
T	Torque
T_r	Reference temperature
t	Random variable
t_s	Student's t
x_m	Mean

Greek Symbols

α	Power adjustment factor
β	Specific fuel consumption adjustment factor
$\mathit{\Phi}_r$	Reference relative humidity
$\triangle$	Confidence interval

Abbreviations

FAME	Fatty acid methyl ester
ASTM	American standard for testing and materials
CI	Compression ignition
DI	Direct injection
B0	Pure Diesel
B5	5% Biodiesel blend with diesel
B10	10% Biodiesel blend with diesel
B20	20% Biodiesel blend with diesel
B100	Pure Biodiesel
CR	Compression Ratio
BSFC	Brake Specific fuel consumption
BP	Brake power
IP	Indicted power
BMEP	Brake mean effective pressure
BTE	Brake thermal efficiency
HC	Unburned hydrocarbons
CO	Carbon monoxide
CO_2	Carbon dioxide
NO_x	Nitrogen oxide
EGT	Exhaust gas temperature
OA	Orthogonal array
CA	Crank angle
BTDC	Before top dead center
ATDC	After top dead center
cSt	Centi-stokes
MJ	Mega joule
KOH	Potassium hydroxide

Chapter 1

Introduction

The objective of this chapter is to provide importance of energy for human life and how it is consumed. This chapter also describes the importance of diesel engine, its problems, its alternative renewable substitutes plant oils, methods of improving the use of plant oils and the properties of biodiesels. Design of Experiments using the full factorial design method and the use of optimization methods are also included by this chapter.

1.1 Energy Scenario of World and Need for Alternative Fuel

The ability of doing work is called Energy. From the genesis of human life on earth, energy becomes the important requirement for their steady growth. After the industrial revolution occurred in the late 18th century, the energy requirement of human life increases at a large rate. As per the reports of International Energy Agency (IEA), compared to today, the energy requirement of world will increase by 50% in the year 2030, out of which 45% of the energy will be required by only two countries China and India. Currently, the major portion of the available energy is consumed by industrial and transportation sectors. As per the energy consumption report of IEA (2007), most of the world's required energy for transportation sector is extracted from fossil fuels as coal (27%), natural gas (23%) and oil (35%), while some portion is extracted from nuclear (5%) and renewable sources (10%) such as solar, wind, tidal, hydro energy and biofuels. After, the invention of internal combustion engines, it became very easy to transport goods as well as people. Due to improvement of standard of living and expansion of industries at various locations, number of cars and trucks on the roads are increasing at a continuous rate. The transportation sector consumes around 30% of the world's total available energy, out of which the 80% of energy is used for only road transport. Presently the energy liberated from the combustion of fuel provides the sufficient motive power for running various prime movers in various sectors. Mostly, Diesel engines are used for various road transports due to its robust design, high thermal efficiency, low consumption of fuel, less fuel cost, high durability and ability to carry heavy loads. The consumption of diesel fuel in India is six times higher than the petrol. However, the efficiency of diesel engine is in the range of 35% to 40%, which means that the complete combustion of fuel is not occurring and loss of generated heat to atmosphere that leads to high exhaust gas temperature. Incomplete combustion in diesel engines produce HC, CO, CO_2,NO_x and smoke emissions in engine exhaust, which are harmful for human life as well as environment. The amount of oil resources and their extraction have some peak period and according to most of studies that peak period is already reached or will be reached in next 10 years. At present, the depletion of fossil fuels and degradation of the environment are the two main problems of the world. As diesel and other petroleum fuels are non-renewable, their alternative should be found out. These alternative fuels should be of low cost, easily available, ready to use, renewable, energy secure, environment friendly and sustainable. This alternative fuel should reduce the environmental pollution without losing the performance of engine. [18]

The consumption of energy in India third largest in the world after USA and China. For the country like India, where the farming is the significant component of country's GDP, the alternative fuel can be extracted from agricultural crops, which are adequately available and less harmful to environment. Biofuels seems to be the best alternative that consist of agricultural waste, biomass, animal fats, alcohols and vegetable oils. Plant oils or Vegetable oils are the best alternative for diesel fuel because their properties are nearer to diesel. Vegetable oil is often referred as triglycerides that consists of three moles of fatty acid and one mole of glycerol. Since the plant oils are produced from the seeds of plants that planted every year, they are crucial renewable sources. Also, CO_2 gases produced by the vegetable oil/biodiesel fueled engine are absorbed by the plants itself during photosynthesis process, which reduces the overall carbon footprint.[18] Rudolph diesel had first used the peanut oil as a fuel in diesel engine in the year 1900. But due to large availability of crude oil and low cost of diesel and gasoline as compared to vegetable oil, the use of vegetable oil was not increased. In the 1940s during the second world war, the use of vegetable oil was started but it was limited. During 1970s, the use of vegetable oil as commercial fuel was started due to rise in petroleum prices. At present, the petroleum fuels are depleting at a faster rate, so the researchers are searching for the better ways of using vegetable oil. [15]

There are two types of plant oils: (1) Edible oil and, (2) Non-edible oil. Edible oil includes Sunflower oil, Peanut oil, Rapeseed oil, Soybean oil, Corn oil, Canola oil and Palm oil etc. Non-edible oil includes Jatropha, Karanja, Mahua, Linseed, Cottonseed and Rubberseed oil etc. Cost of vegetable oils are higher than the diesel fuel. Edible oil is mainly used for food purpose. Edible oils are the first-generation oils that can be used for producing biodiesel but its more use may produce adverse effects on supply of edible oils for food. Non-edible oils which are called as second-generation oils that should be used for biodiesel production since they can be produced from the waste lands which are not suitable for cultivation of food crops. As the cost of non-edible oil is less than the edible oil, it can decrease the production cost of biodiesel substantially since the cost of the feedstocks contributes 70 to 75% of total biodiesel cost. The type of feedstock used for producing biodiesel depends upon local climate, terrestrial conditions, type and amount of farming practices.[26] Now, the microalgae are appeared as the third-generation feedstock for biodiesel production. These microalgae are the microorganisms that uses the water, sunlight and CO_2 and convert it into the algae biomass through photosynthesis. Compared to conventional crops, microalgae made biomass more efficiently. The oil content and oil yield of microalgae is more than edible and non-edible oils. But due to requirements of large bioreactors and high strains of oil yielding, the cost of microalgae is more than edible and non-edible oils. [18]

1.2 Problems with Plant oils and Processes to Improve the Use of Plant oils

Plant oils should not be used in pure form in diesel engine for long time as it causes some serious problems such as choking of fuel line, fuel filters, deposition of carbon particles on fuel injector, cylinder head and piston crown, poor atomization, accumulation of fuel, sticking of piston ring, possibility of knocking and polymerization of lubricating oil. These problems are occurred due to some undesirable properties of plant oils such as high viscosity and density, low volatility, 10% lower heating value and instability of unsaturated fatty acids. High viscosity of plant oil causes problem in fuel pumping and spray pattern. Compared to straight plant oils, better performance is occurred for long time with the engine fueled with blends of plant oils and diesel. The literature shows that neat plant oil can be used for short term running on diesel engine, but for long term running it affects seriously to the various important parts of the CI engine and lubrication oil. Although the plant oils based biodiesels seems to be best alternative, but its corrosive and wear effects on the automobile components need to be considered. [25, 30]

The problem occurred with use of straight plant oils in the compression ignition engine can be reduced by four methods: (1) Pyrolysis, (2) Dilution, (3) Microemulsion and (4) Transesterification. [18, 29]

1. **Pyrolysis** – In pyrolysis process, the thermal decomposition of the organic compounds of the vegetable oils or animal fats takes place in the reactor with the presence of catalyst and absence of oxygen. This thermal decomposition of vegetable oil will produce alkadines, alkenes and carboxylic acids. The final product of pyrolysis

reaction has higher cetane number and lower density, viscosity and water content as compared to diesel. This reaction increases the carbon content and ash content in the final product. This process is non-polluting, but the cost of equipment and the temperature requirement are higher that increases the capital cost.

2. **Dilution** – In dilution process, the vegetable oil is directly diluted with conventional diesel fuel for reducing the viscosity without any chemical process. According to literature, instead of pure vegetable oil, 20/80 vegetable oil/diesel blend showed little drop in diesel engine power. Vegetable oil can be diluted with 4% ethanol to increase BTE and reduce BSFC. Due to lower boiling temperature of ethanol, it can help to start the combustion of fuel. Use of this diluted fuel can be used for short periods, but for long term it affects the engine components badly because some properties of diluted vegetable oils are not matching with ASTM standards. Dilution of vegetable oil does not change the molecular composition of vegetable oil and so the poly-unsaturation character of fatty acids, high viscosity and low volatility of vegetable oil remains as it is.

3. **Microemulsion** – Emulsion is the mixture of two or more liquids that are immiscible at normal temperature and pressure. Microemulsion consists of three components: aqueous phase, oil phase and surfactant. Oil phase is made of the mixture of different hydrocarbons and olefins. Salts are consisted by aqueous phase. In microemulsion process, using two immiscible liquids such as ethanol and methanol and ionic or non-ionic amphiphiles, the colloidal balanced dispersion of optically isotropic fluid micro-structure having dimensions in the range of 1–150 nm is formed for reducing the viscosity of vegetable oil. The resulted product has some properties nearer to diesel.

4. **Transesterification** – Transesterification is the reversible process with the conversion efficiency of 90-95%, which is best for improving the use of vegetable oil in diesel engine as it changes the molecular structure of oil. In this process, one mole of triglycerides (vegetable oil) reacts with the three moles of alcohol specially methanol in the presence of catalyst to form one mole of fatty acid methyl ester (FAME) and one mole of glycerol. The catalyst increases the solubility of methanol for enhancing the rate of reaction. Here the triglycerides are step-wise converted into diglycerides, monoglycerides and then into FAME (Biodiesel). The by-product glycerol is used in cosmetic industries. The final biodiesel produced through this process consists of around 95% FAME with the remained percentage consists of residual alcohol, catalysts, unconverted glycerides. The ethanol can be used in this process, but in most of the industrial processes methanol is used due to its low cost, therefore it is called as FAME. The catalysts used in this process are of two types: acid catalysts and alkaline catalysts. Hydrochloric, sulfuric and phosphoric acids are used as acid

catalysts, while the potassium hydroxide and sodium hydroxide are used as alkaline catalysts. Acid catalytic reaction are time consuming and so they are used for reducing the fatty acid levels of oils to range required for alkaline catalytic reactions. Alkaline catalytic reactions are faster than acid catalytic, but it requires the fatty acid level of vegetable oil in the range of 0.5% to 3%. In non-catalytic reactions, the catalyst is not used, which makes easy to separate the free glycerol and excess alcohol from final biodiesel. But due to requirement of high pressure, temperature and more alcohol, the non-catalytic reactions are costlier. The biodiesel formed through transesterification has high viscosity, density, flash point, cetane number and low calorific value.

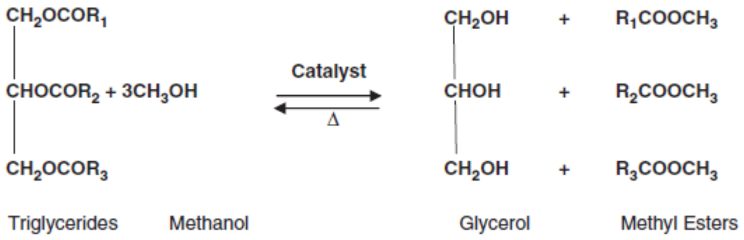

Figure 1.1: Transesterification reaction with plant oils and alcohol [10]

1.3 Advantages and Disadvantages of Biodiesel

1.3.1 Advantages

- Biodiesel is environment friendly, renewable, biodegradable, non-flammable, non-toxic with zero sulphur content and very low aromatic compounds. [18]
- Up to 20%, biodiesel can be mixed with diesel without engine modifications and with little loss in performance. [29]
- Due to 11% more oxygen content and high cetane number, Biodiesels have lower amount of hydrogen and carbon content than diesel. This reduces the HC, PM and CO emissions from engine exhaust. [28]
- Due to high flash point of biodiesel, it is safer to handle, transport, use and store the biodiesels. [18]
- Due to better lubricating properties of biodiesels, the engine wear debris in lubricating oil is substantially reduced.
- Unused waste lands of rural areas can be used for cultivating non-edible oil plants for producing biodiesels. This will help the rural development by rising the employability of people and use of waste lands for non-edible oil production.

- Crude oils are produced after the hundred to thousand years of decomposition of various dead creatures and plants in the earth's crust and they are available at certain locations of earth. For pure diesel, the crude oil is to be extracted from earth by kilometers of drilling and then this crude oil is to be refined in the refinery. The plant oils are extracted from the plants growing at any location of earth, which makes it readily available.
- Compared to diesel fuel, biodiesel reduces the global warming effect by the net reduction in CO_2 emissions during its whole life cycle.
- Biodiesel can be made from waste cooking oils, frying oils and used oils.

1.3.2 Disadvantages

- Biodiesels are produced from variety of plant oils. So, each biodiesel has different quality, which makes the user unable to select the best biodiesel. [18]
- Due to significantly higher viscosity of biodiesel than diesel, the atomization of biodiesel is poor and accumulation of fuel occurs. This will cause the incomplete combustion and the possibility of knocking. [28]
- More percentage of biodiesel in the blend degrades the engine performance. Also, due to lower heating value of biodiesel, the specific fuel consumption of biodiesel is 3-10% higher than the diesel.
- Engine power and speed are reduced by using biodiesel.
- The NO_x emissions of biodiesel fueled engine are higher than diesel because of higher oxygen content and advanced injection timing for biodiesels. [29]
- Biodiesel reduces the premixed combustion phase, which reduces the heat release rate of combustion.
- Long-time use of biodiesel in the CI engine leads to corrosion of various engine static components such as fuel pump, fuel tank, cylinder liner and dynamic components such as piston rings, piston, connecting rod, engine valves, which increases the maintenance of engine.
- Use of edible oil based biodiesels for commercial purpose may rise the problems of lack of supply of edible oil for food purpose.

1.4 Production of Biodiesel

1.4.1 Production of Biodiesel in the World

In the developed countries like USA, Britain, Germany, France, Australia, the use of biodiesel is catching its momentum for reducing the carbon footprint since these countries are more contributing to the global warming. Government encourages to use biodiesel by providing subsidy. In USA, the cost of biodiesel is \$3 per gallon, which is reduced to \$1.8 per gallon by providing subsidies. According to Energy Independence and Security Act, the production of plant oil based biodiesel in the year 2009 was 0.5 billion gallons per year.[28] USA is producing 75 million tons of biodiesels annually. Mostly soybean oil is used for producing biodiesels in US. Up to 20% biodiesel blend is used in USA. European countries use rapeseed oil for biodiesel production. Germany is producing around most of its biodiesel from rapeseed oils. It uses the blend of 7% biodiesel with diesel. The price of biodiesel is lower than diesel in Germany. Brazil is producing 46 million litres of biodiesel from soybean, sunflower and castor oil. Indonesia is exporting biodiesel to Germany, Japan and USA. Malaysia is the largest producer of palm oils as the tropical areas are suitable for producing palm oil. Malaysia uses B5 biodiesel for commercial transportation. Zimbabwe is planting more than 4 million Jatropha plants every year. Thailand is producing 2 million liter of biodiesel from Jatropha, palm and coconut oil. The availability of biodiesel is more in rural areas due to more agricultural waste as compared to urban areas.

1.4.2 Production of Biodiesel in the India

As the India's population is the second largest in the world after China, the energy requirement of the India is increasing at a faster rate day-by-day. As India has not more petroleum resources, the 70% of total required petroleum is imported by India to continue its steady development. To reduce this foreign petroleum load, the alternative low-cost fuels should be used which are available in vast amount. In rural areas, people uses diesel engines for their electricity needs due to un-reachability of electricity grids. As 60-65% of the Indian population are farmers, the biodiesels produced from agricultural plants and waste seems to be best alternative because of its vast availability and renewability. As diesel engines are used in various commercial, agricultural and industrial areas, biodiesel can substantially reduce the use of diesel in CI engines. Mixing of 5% biodiesel with 95% diesel can save the diesel cost of Rs. 4000 crores annually. In India, there are mainly two vegetable oils are used for biodiesels: Jatropha and Karanja biodiesel. These non-edible vegetable oils can be grown into waste lands, which is not suitable for edible food crops. The planning commission of India has planned strategy to use 20% biodiesel with diesel by producing 14 million tons of biodiesel annually. Karnataka government has provided several thousand ha of waste lands to farmers for the cultivation of Karanja (Pongamia) plants. Collaboration of Indian railways and IOCL has been done for producing Jatropha and pongamia plants in waste lands. As the cultivating cost of Pongamia and Castor oil is more, the plantation of Jatropha is increased. Gujarat government is planned to provide 40 lakh ha of waste lands to farmers for cultivation of Jatropha plants.

1.5 Properties of Biodiesel

The properties of biodiesels largely depend upon the type of feedstock used for its production. Therefore, the properties of biodiesels vary from biodiesel to biodiesel. Most of the biodiesels consist of normal paraffins having straight chains, while some biodiesels consist of substantial amount of paraffins having branches. Properties of biodiesels were specified according to ASTM standards and European Committee for Standardization (CEN). The properties of B100 is measured as per ASTM D6751, while the properties of biodiesel blends of up to B5 and B6 to B20 are measured according to ASTM D975 and ASTM D7467 respectively. Some important properties of the biodiesels are discussed as follows: [18, 28]

1. **Density** – Density is the ratio of mass per unit volume. As the metering of fuel by fuel pumps and fuel injectors is done on the basis of volume, not mass, the amount of fuel injected in the combustion chamber is significantly affected by the fuel density. The density of biodiesel is slightly higher (2 to 3%) than the diesel fuel due to unsaturation of fatty acids. For the same volume of both fuels, more mass of biodiesel is consumed during engine operation. Also, the energy content of biodiesel is lower than diesel, therefore for the more mass of the biodiesel injection, the supply of actual energy is lower than diesel. Density of biodiesel is measured as per ASTM D1298. The specific gravity (ratio of density of fuel to density of water) of biodiesels is in the range of 0.86 to 0.90, while it is 0.85 for diesel according to ASTM D-287.

2. **Viscosity** – Viscosity is internal friction between two fluid layers moving at a different velocity, which opposes its movement. It describes the ability of fluid to flow. As the molecular mass of biodiesel is high, it has 11-14 times higher viscosity than diesel. This high viscosity results in improper atomization, smaller spray angle of injection and so the fuel droplet size will be larger, which requires more time to vaporize and increases the ignition delay. High viscosity will cause incomplete combustion and produces carbon deposits on various engine components. At low ambient temperature, the high viscosity causes the engine starting problems especially for B100. By changing the alcohol for transesterification reaction from methanol to propanol, Slight increase in viscosity of final FAME occurs. Viscosity

can be reduced by heating the fuel initially. Viscosity of biodiesel is measured as per ASTM D445.

3. **Flash point** – It is the temperature of fuel at which, it will burn during compression stroke due to sparking or fuel injection into high temperature air. Biodiesels have higher flash point than the diesel due to its lower volatility. Due to this, biodiesels are easy to handle and store. Low volatile fuels have high flash point. Vegetable oils have higher flash point than biodiesels. The flash point of biodiesels is more than 90 °C. Flash point decreases with increase in the residual alcohol remained in the final biodiesel due to improper washing and purification. Flash point is measured according to ASTM D93.

4. **Cloud point** – It is the temperature of fuel at which the forming of crystals in fuel and the separation of wax content of oil are starting due to low temperature. A higher cloud point partly or completely solidifies the fuel during cold weather, which can block the fuel lines, fuel pumps, fuel filters and the starving of engine occurs due to reduced flow of fuel. The cloud point of biodiesels is higher than diesel, which makes it difficult to use in cold weather conditions. Higher cloud point of biodiesel is due to saturated fatty acids and longer (more than C_{12}) carbon chain. Cold conditions performance can be increased by the unsaturated fatty acids in biodiesel feedstocks. Blending of certain types of biodiesels can improve the cold weather performance i.e. Palm biodiesel's cold performance can be increased by mixing it with Jatropha biodiesel. Cloud point is measured as per ASTM D2500.

5. **Pour point** – It is the lowest temperature at which the wax formed in the fuel during cold weather is enough to flow the fuel. The pour point of biodiesel is higher than diesel. It is measured as per ASTM D97.

6. **Cetane number (CN)** – It describes the ability of fuel to burn itself, when it was injected under high pressure through fuel injector in the case of diesel fuel. High CN reduces the ignition delay, which will cause better combustion of fuel. The CN of biodiesels is higher than diesel due to long chain of hydrocarbons and zero aromatic groups. The feedstocks with more amount of saturated fatty acids increases the CN of biodiesel. The CN of the biodiesel is specified by ASTM D613.

7. **Oxidative stability** – It is the property of fuel to react with atmospheric oxygen when exposed to air. Higher oxidation of fuel may form residues in fuel, which can chock the fuel line and filters. Due to presence of carbon atoms with double bonds and more amount of unsaturated fatty acids, the biodiesels are more oxidative than diesel. Oxidative stability also depends upon the storage time of the biodiesel. In oxidative reaction, the hydrogen atom is extracted from the carbon atom nearer to

the double bond. Then the allylic hydroperoxides are formed through the reaction with oxygen molecule. Then the subsequent secondary oxidation reactions along with chain propagation and isomerization are occurred with the final products such as carboxylic acids, alcohol and aldehydes. Oxidative stability is measured as per ASTM D6751.

8. **Acid value** – It shows the amount of free fatty acids (FFA) confined by the fuel. It is defined as the amount of base required for neutralizing the free fatty acids of fuel. The naturally occurred unsaturated fatty acids in the vegetable oils and other fuels will increase the acid value. Due to higher acid value of biodiesels than diesel, it causes more corrosion of engine components as compared to diesel. High acid value can reduce the useful life of fuel pump and fuel injectors due to degradation of fuel with using. Use of alkaline catalysts for producing biodiesel can help to reduce its acid value as the residual alkaline catalysts can neutralize the acidic character of biodiesel. Acid value is measured as per ASTM D664.

9. **Lubricity** – Lubricity means the prevention of direct metal to metal contact during relative motion by forming the small layer, which can absorb the carbon deposits, wear metal debris and shocks. Due to improvement of injection pressures, number of injections per cycle and injection cone angle, the modern fuel should have good lubricity properties. Biodiesels have improved lubrication properties than diesel since polyunsaturated character of vegetable oil can be reduced by transesterification. The residual monoglycerides in the biodiesel have good lubricity, but they have poor cold weather performance. Reduction of impurities (monoglycerides) in final biodiesel using purification process decreases the lubricity properties. High lubricity can reduce the loss of power and increase the mechanical efficiency.

1.6 Design of Experiments

1.6.1 Introduction to DOE

When any experiment includes many input parameters, then effect of each parameter on output result will require many number of experiments, which will be costly and time consuming. The output of the analysis will be different from product to product. In the analysis of any product/process, our aim is to minimize the cost involved and maximize the performance, i.e. In the machining of any raw material, our aim is to maximize the material removal rate and minimize the tool wear. Taguchi method provides the systemic analysis of given input parameters and gives the optimum combination of input parameters for which the output will be maximized or minimized. Taguchi method is used to design the number of experiments for processes, where the performance of process depends on many input parameters. Actually, the first use of this method was related to the maximization of the agricultural productivity. In that, for the given input parameters such as type of land, type of fertilizer, quality of seeds, purity of water, which combination of the input parameters will give maximum agricultural crops without losing the quality. The number of factors involved by engineering processes are more and the interaction among these factors will lead to large number of combinations of factors. Taguchi developed a distinct set of designs, in which the specially designed orthogonal arrays are used to find the optimum number of experiments required for finding the effects of given input factors.

First method regarding the design of experiments was introduced by Sir R. A. Fisher in the year 1920s, in which all the possible combinations of the involving factors were proposed by full factorial design. Design of experiment of any product or process includes the control parameters known as control factors and output parameters known as response variables. Each factor has two or more levels (absolute values), which decides the complexity involved in experiment. The factors are independent variables, while the response parameters are dependent variables. The factors having two levels, upper and lower level will result in easier experiments. For a performance and emissions testing of diesel engine, the control factors include compression ratio, injection pressure, injection timing etc, while the response variables include specific fuel consumption, thermal efficiency, smoke, CO, HC emissions etc. Control factors can be of two types: [27]

1. Controllable factors – The factors whose levels (values) are properly specified and can be controlled by us during the experiment/process, so the final output can be modified, those factors are called as controllable factors. i.e. compression ratio, injection pressure for engine testing, length and diameter of the metal piece during machining, the amount of sugar, flour, salt added during baking.

2. Uncontrollable factors (Noise factors) – The factors whose levels are not properly specified and cannot be controlled by us during the experiment/process, so the final output cannot be modified, those factors are called as uncontrollable factors or noise factors. i.e. atmospheric temperature, humidity during engine testing, vibrations, shocks occurred during machining of metal piece.

1.6.2 Full Factorial Design

For measuring the temperature acting at two points A and B in the flow of water through the horizontal pipe, we will require to conduct experiments at two points with thermocouple for temperature measurement. Suppose the temperatures are 50°C and 40°C at the points A and B respectively. Here the number of factor is one – temperature and number of levels of this factor are two. Suppose, any process involves two factors A and

B with two levels ‘0’ (low level) and ‘1’ (high level) for each factor. The total number of experiments for this process will be four. This is called as $m^k = 2^2$ factorial design, where the power ‘k’ represents the number of factors and base ‘m’ represents the no. of levels of each factor. Similarly, for the process involving 3 factors A, B and C with two levels ‘0’ and ‘1’ for each factor, the number of experiments for this design will be $2^3 = 8$. This is called as 2^3 factorial design as shown in table 1.1. [27]

Table 1.1: Number of experiments obtained by 2^3full factorial design

Experiment Number	A	B	C
1	0	0	0
2	0	0	1
3	0	1	0
4	1	0	0
5	0	1	1
6	1	0	1
7	1	1	0
8	1	1	1

For the process involving seven factors with two levels ‘1’ and ‘2’ for each factor, the total number of experiments using full factorial design will be $2^7 = 128$. For the process involving four factors with three levels for each factor, the total number of experiments using full factorial design will be $3^4 = 81$. Here we have to vary one factor level at a time by keeping all other factors as constant. This is also called as one factor at a time (OFAT) method. We have to conduct all possible experiments and from them, we have to conclude the optimum combination, which is very costly and time consuming. By the method called partial factorial design, some limited number of combinations from full factorial design are selected to reduce the no. of experiments by keeping minimum effects on output. Taguchi’s orthogonal array design has solved this problem by providing standard method.

1.7 Optimization Methods

Optimization is the way of getting best and possible solution from available choices. In daily routines, there are many situations comes where we have to select the best one from available choices. The selection or choice becomes easy, when it consists of less criteria. For example, if we want to buy a motorcycle on the basis of price, then after referring the details of motorcycles of various company, we will buy the one which has lowest price. Now if one more parameter like performance comes as selection criteria in addition to price, then the decision becomes complex. Different criteria have their different satisfaction values e.g. For purchasing of motorcycle, we want the maximum performance, more lifespan, less fuel consumption, less emission and least price. These type of complex selection problems require some optimization methods, which will give the best result or choice that has maximum satisfaction. A optimization problem has alternatives, attributes or criteria and the objective. Consider the following optimization problem given in table 1.2.

Table 1.2: Optimization of best vehicle model based on four attributes

Weight	0.1	0.4	0.3	0.2
Model	Style	Reliability	Fuel economy	Cost
Ciaz	7	9	9	8
Etios	8	7	8	7
Vento	9	6	8	9
Xcent	6	7	8	6

The available choices in the given problem are called as alternatives. The parameters on basis of which the selection has to be done are called as attributes or criterias. The required level of satisfaction in each attribute is called as objective. In the above problem we have to buy a car based on four parameters. Here, the number of models are alternatives, while the style, reliability, fuel economy and cost are attributes. The level of satisfaction of attributes are different based on requirement. Style, reliability and the fuel economy of car should be high, while the cost of the car should be low. This type of problem that consist of multiple attributes for optimization is called as Multi attribute decision making (MADM). MADM is the process of solving the real world problems on the basis of quantitative/ qualitative attributes in a determinate/ indeterminate environments to propose a set of actions/ choices from the available options. MADM was invented by satty in 1980. Here, the information about the pairwise comparison of alternatives with respect to the given criteria is used for optimization. This MADM is used for the selection or evaluation of process, where the number of alternatives are finite. During selection of alternative, the perception of the decision maker is taken into consideration. According to universal law, there is no thing on this earth, which is best in every aspects. So in the MADM problem, we have to give the relative weightage to each of attribute. Maximum weightage will be given to the attribute that required the highest level of satisfaction, while the minimum weightage will be given to the attribute having lowest level of satisfaction. The summation of all weights must be one. Every attribute has different measurement units e.g. fuel economy is measured in kW/ kg of fuel consumed, while the cost is measured in Rupees. So in the optimization method we have to normalize them by converting them in to non-dimensional numbers. Different optimization methods have different ways to convert attribute values in to non-dimensional numbers. There are many methods for solving MADM e.g. Analytic Hierarchy Process (AHP), Topsis, Vikor, Promethee. But each of these optimization methods is working on four steps:

1. Collection of information
2. Quantification of information
3. Modelling
4. Action

For the our experimental study of different biodiesels on the performance, combustion and emission of CI engine, we are using two MADM based methods: Topsis and Promethee. The detailed discussion of these two Topsis and Promethee methods is done in subsections 4.3.1 and 4.3.2 respectively.

1.8 Organization of Report

This chapter consists of introduction of biodiesel, its properties, design of experiments by full factorial method and use of optimization method. Second chapter consists of the detailed literature review on the performance, emission and wear analysis of biodiesel fueled CI engine. It also consists of papers related to use of Taguchi method for decreasing the number of experiments and finding the optimum combination of engine operating variables. Problem definition and the objective of the present study are also included by second chapter. The third chapter consists the details of experimental setup and experimental methodology for the performance, combustion and emission analysis of different biodiesel blends. It also consists of the repeatability of experiments and the uncertainty analysis. The fourth chapter consists the results and discussion of the first and second phase of experiments. The application of Topsis and Promethee methods for assigning the ranking to the different biodiesel blends according to the results of first and second phase of experiments are also discussed in fourth chapter. The fifth chapter consists the conclusion of present research work and also the future work that can be carried out for knowing the various effects of the optimum blend on engine parts for long term experiments.

1.9 Closure

In this chapter we have discussed the energy scenario of world, need of alternative fuel, processes of improving use of plant oils in CI engine, properties of biodiesels and production of biodiesels in various countries. Also, the design of experiments using full factorial method and the use of optimization methods have been discussed.

Chapter 2

Literature Review

This chapter includes the details of various experiments and researches conducted by different researchers regarding the use of pure plant oils/biodiesel and their blends with diesel in the compression ignition engines. It includes the review on the effect of plant oils/biodiesels on the performance, emission and the wear of the CI engine. It also includes the papers regarding the use of Taguchi method for designing of experiments conducted on the engine. The definition of the problem and objective of present study are also discussed.

2.1 Engine Performance and Emission

After the industrial revolution, the petroleum reserves are proved to be 'Black Gold' for the continuous growth of industries. Especially, when the diesel is started as a commercial fuel for transportation, the establishment of industries at different locations becomes possible. Due to low cost and high efficiency of diesel, most heavy-duty transportation vehicles are running on diesel fuel. But as the diesel fuel is non-renewable and also produces harmful emissions, it is necessary to find its alternative. Because of enhancing rates of use of petroleum fuels for industries as well as transportation, world is currently faces the problems of depletion of petroleum fuels and environmental pollution. According to Euro IV (2010) norms, the exhaust gases produced by diesel engines (gross weight greater than 3500 kg) must contain the amount of CO, PM, HC and NO_x emissions as 1.5, 0.02, 0.46 and 3.5 g/kWh respectively. As the petroleum reserves are limited, researches are trying to find the best alternative fuel. Many types of alternative fuels are identified till now, but they cannot substitute the diesel fuel due to significant variation of properties between them and diesel. Most of them requires the huge modification of existing engines and cannot be available in commercial fueling stations like diesel. Biodiesels derived from plant oils through transesterification process can substitute the diesel by up to 20% with minimum loss of performance. As the non-edible plant oil plants can be cultivated in the waste lands, the need of diesel fuel by rural areas can be reduced by plant oils based biodiesels. Many researches and experiments are conducted on the use of biodiesel in CI diesel engine.

Nwafor and Rice, [1] studied the performance of rapeseed oil blends in diesel engine. In the recent scenario of higher fossil fuel use and environmental pollution, vegetable oil can be used as a substitute of diesel, but the 100% of use of vegetable oil as a substitute causes several engine problems. The long-term use of vegetable oil causes the carbon deposits on cylinder head, choking of fuel lines and degradation of lubricating oil properties. They conducted tests on single-cylinder, air cooled, four-stroke engine using 0%, 25%, 50%, 75% and 100% blends of Rapeseed oil with pure diesel at an engine speed of 3000 rpm and Engine torque of 9.65 Nm. The test results showed that power output of engine was decreased when pure rapeseed oil is used and the power output was increased with increase in percentage the diesel in the blend. The peak cylinder pressure was decreased for neat rapeseed oil. With respect to pure rapeseed oil, the ignition delay period was reduced and cylinder pressure was increased for 50/50 blend. The duration of injection was decreased with increase of percentage of diesel in the blend. Due to high viscosity and low heating value, the vegetable oil was vaporized at a slower rate. With increase in percentage of rapeseed oil in blend, the brake specific fuel consumption and brake thermal efficiency were increased. The mechanical efficiency was high for neat rapeseed oil and 25/75 diesel/rapeseed oil blend. The HC emissions were decreased and CO emissions were increased for more percentage of rapeseed oil in blends. For neat rapeseed oil and 25/75 diesel/rapeseed oil blend, the HC emissions were low and the CO emissions were high. The 50/50 blend was considered as optimum blend.

Wang et al.,[2] conducted experiments on two-cylinder, four-stroke, air cooled diesel engines using pure diesel, pure vegetable oil and blends of vegetable oil with diesel in proportion of 25%, 50% and 75% to study performance and emission characteristics. The engine speed was 1500 rpm and load on the engine varies as 0%, 25%, 50%, 75% and 100%. With increase in load, the brake power was increased and the BSFC was decreased. Engine power output and BSFC were almost same for pure diesel, vegetable oil and its blends. The exhaust temperature was highest for 25/75 diesel/vegetable oil blend. At low loads, the CO emissions of vegetable oil and its blends were higher than diesel, while at high loads, it became low for vegetable oil and its blends due to high cylinder temperature. CO emissions were lowest for 75/25 diesel/vegetable oil blend. The CO_2 emissions of diesel fuel were higher than vegetable oil and its blends due to high oxygen content of vegetable oil for the carbon content in the same volume of fuel at same load. HC emissions were increased with increase in engine load due to less oxygen available for combustion at high loads. Except 50/50 diesel/vegetable oil blend, all oil blends had low HC emissions than diesel. The NO_x emissions of diesel fuel were higher than vegetable oil blends due to lower heating value of vegetable oil. NO_x emissions were lowest for pure vegetable oil.

Jindal et al.,[5] studied the effect of fuel injection pressure and compression ratio on the performance of single cylinder, water cooled, DI engine using pure Jatropha Methyl Ester (B100) biodiesel. Comparisons were done with base tests conducted with standard diesel. For diesel, the testing conditions were 210 bar injection pressure and 17.5 compression ratio, while for B100, tests were conducted at three injection pressures (150 bar, 200 bar and 250 bar) and at three compression ratios (16, 17 and 18) for each injection pressure. For B100, the BSFC was decreased and Brake thermal efficiency was increased with increase in compression ratio, injection pressure and engine load. With respect to diesel, the BSFC and BTE of B100 were increased by 10% and 8.9% respectively, at compression ratio 18 and fuel injection pressure 250 bar. Compared to diesel fuel, HC, NO_x emissions, smoke density and exhaust temperature were decreased, while CO, CO_2 emissions were increased for B100 fueled diesel engine. For B100, with increase in compression ratio, the HC, CO_2 emissions and exhaust temperature were increased, whereas smoke density and CO emissions were decreased. Also for B100, with increase in injection pressure, CO, CO_2 and exhaust temperature were increased, while HC, NO_x and smoke emissions were decreased. For using 100% biodiesel as fuel, the diesel engine should be running at high compression ratio and injection pressure.

Patel et al.,[6] conducted experimental investigation on reduction of NO_x and HC emissions of CI engines using Jatropha biodiesel and Diethyl ether (DEE) additive. Although the biodiesel can reduce the exhaust emissions such as HC, CO and smoke, but it is unable to reduce the NO_x emissions due to 11% more oxygen for biodiesel. Literature shows that addition of 1-2% oxygenated additive diethyl ether can reduce the NO_x emissions significantly. The authors were conducted experiments at various engine loads of 5%, 25%, 50%, 75% and 100% with various biodiesel blends B0, B5, B10, B15, B20, B25 and B30. From that, the B20 biodiesel blend was optimized. Using B20 (20% Biodiesel blend), the efficiency and emissions such as CO, HC, CO_2 and NO_x were decreased, while the BSFC and BSEC were increased. The emissions were decreased due to biodiesel's more molecular oxygen content and high cetane number, while the BSFC and BSEC were increased due to biodiesel's low calorific value, low volatility, high density and viscosity. Except NO_x emissions, most of the emissions of B20 blend met the EURO IV standards. So, the tests were conducted with 0% to 5% (in the step of 1%) addition of DEE in blend B20. Using DEE, the reduction in PM and smoke emissions was significant due to 21% more oxygen of DEE than diesel. Compared to B20 blend the thermal efficiency and BSFC were increased by 6.52% and 3.87% respectively, while the BSEC was reduced by 7% for addition of 4% DEE in B20 blend. Except NO_x emissions, the percentage reductions in other exhaust emissions were not quite large. NO_x emissions were reduced by 40% and 25.08% compared to diesel fuel and B20 blend respectively. Combustion analysis of DEE-B20 blends showed that for 4% DEE, ignition delay period, rate of pressure rise was decreased which resulted in smooth combustion.

C. Rakopoulos et al.,[9] conducted experiments on single cylinder, DI, Ricardo/ Cussons 'Hydra' diesel engine using blends of 10/90 and 20/80 diesel fuel with various vegetable oils and biodiesels of various origin. The vegetable oils and bio diesels used in these experiments were cottonseed oil, soybean oil, sunflower oil and correspondingly their methyl esters, as well as rapeseed oil methyl ester, palm oil methyl ester, corn oil and olive kernel oil. The tests were conducted at an engine speed of 2000 rpm with 38% (medium load) and 75% (high load) of full load. Base line tests were conducted with pure diesel for comparison of the performance and emissions of all vegetable oils and bio diesels blends. Due to differences in calorific values of all test fuels, the comparisons were done at same brake mean effective pressure, i.e. load and speed. Compared to pure diesel, the smoke density, CO, NO_x emissions were lower, while the BSFC and BTE were slightly higher for various biodiesel blends. Compared to pure diesel, the NO_x emissions were lower, while the smoke density, CO, BSFC and BTE were higher for various vegetable oil blends. The HC emissions of biodiesel and vegetable oil blends were high at medium loads and showed not any definite trend at high loads. At high loads, the amount various engine emissions were increased. Compared to 10/90 blends, 20/90 blends of various biodiesels showed more decrease in emissions. At high loads, the BTE showed not any consistent trend. Highest reduction in smoke density, NO_x, HC were caused by cottonseed biodiesel, while highest CO emissions were caused by soybean biodiesel. Sunflower biodiesel showed least BSFC and highest BTE at medium and high loads. Except the slight increase in smoke density and CO emissions for vegetable oils, all the biodiesels and vegetable oils can be used safely in diesel engine in 20/80 blending ratio.

Agarwal et al.,[10] conducted experiments on biodiesel blends (B10, B20 and B50) fueled two-cylinder, air cooled, DI diesel engine (rated speed 1500 rpm at rated power 9 kW) using 15% exhaust gas recirculation to reduce NO_x emissions. They used the rice bran oil as vegetable oil in this study and viscosity, specific gravity and flash point of an oil were reduced through Transesterification process. Compared to pure diesel, biodiesel fueled engine produced less HC, CO and PM emissions, but it produced more NO_x emissions. Presence of more molecular oxygen content in biodiesel increases the NO_x emissions, which can be decreased by EGR because it lowers the oxygen concentration and provides the more specific heat charge that leads to lower flame temperature in combustion chamber. The results were compared with tests of pure diesel with and without EGR. When EGR was used with pure Diesel, the smoke opacity, PM, CO, HC emissions and BTE were increased, while the BSFC, BSEC, exhaust gas temperature, NO_x emissions were decreased as compared to without EGR. With respect to pure diesel with EGR, biodiesel blends with EGR showed that the exhaust gas temperature, smoke opacity, BSEC, CO, HC and NO_x emissions were decreased and BSFC, thermal efficiency were increased. The 11% more oxygen content of biodiesel was sufficient for complete combustion of carbon particles that came with recirculated exhaust. With EGR, increase in blend ratio would increase BSFC, smoke opacity, NO_x emissions and decrease HC, CO emissions. The results showed that the B20 biodiesel blend with 15% EGR would be the optimum combination that enhances the thermal efficiency and reduces emissions. EGR can reduce the engine durability and affect adversely on lubricating oil.

Rahman et al.,[13] carried out the experimental research of performance and emission of four cylinder, four-stroke, air cooled, indirect injection Mitsubishi Pajero (rated speed 4200 rpm at rated power 55 kW) diesel engine using two biodiesels. Biodiesels used in this study were Jatropha curcas (JB) and Moringa oleifera (MB) methyl esters. The physicochemical properties of these biodiesels and their blends were agreed with EN 14214 and ASTM D6751 standards and the results of the experiments with 10% biodiesel blends (JB10 and MB10) were compared with base tests of diesel fuel. The viscosity, density, cetane number and calorific value of MOME were higher than JCME. The engine was operated at full load conditions with the varying speeds from 1000 to 4000 rpm. Each experiment was repeated three times and results were calculated by averaging. For the entire range of speed, the MB10 and JB10 blends produced 4% and 5% lower brake power respectively, compared to diesel fuel due to lower calorific value and high viscosity of biodiesel. The brake specific fuel consumption of MB10 and JB10 were 5% and 3% higher than diesel due to low energy density of biodiesel. Compared to pure diesel, biodiesel blends MB10 and JB10 produced 11% and 14% less CO emissions respectively, and produced 12% and 16% less HC emissions respectively. This was due to the 11% more molecular oxygen content for the biodiesel than that for diesel. But compared to diesel, the biodiesel blends MB10 and JB10 fuels produced 9% and 7% more NO_x emissions respectively, due to higher flame temperature and produced 5% and 7% more carbon dioxide emissions respectively. So, the biodiesels J. curcas and M. oleifera can be replaced the conventional diesel for improving the performance and reducing the emissions. The MB10 blend gave high performance, while the JB10 blend produced least exhaust emissions.

Ozsezen et al.,[14] conducted the experimental investigation on inline six-cylinder 6 L Ford Cargo, water cooled, DI diesel engine (rated speed 1500 rpm and rated brake torque 335 Nm) using two different biodiesels waste palm oil methyl ester and (WPOME) and canola oil methyl ester (COME). The results were compared with the base tests conducted with petroleum based diesel fuel (PBDF) at constant speed of 1500 rpm under full load condition. Compared to PBDF, the brake torque was slightly reduced for the engine fueled with COME and WPOME, while the bsfc was increased by 6.18% and 7.48% respectively, due to high density, viscosity and 8-9% lower heating value of both biodiesels. Compared to PBDF, the brake thermal efficiency was slightly decreased for COME and WPOME, while the brake power was decreased by 2.7% and 2.5% respectively. Both biodiesels were produced nearly same maximum brake torque and brake thermal efficiency. Due to high oxygen content, bsfc, cetane number and advance start of injection, the peak cylinder pressures were higher and occurred at 0.25° CA earlier for both biodiesels as compared to PBDF. The cylinder gas pressure for both biodiesels varied smoothly without any pressure waves under full load condition, while for the PBDF, the cylinder pressure varies unsmoothly. Due to slow vaporization rate and advanced SOI, the start of combustion (SOC) for both biodiesels was 2° CA earlier BTDC as compared to PBDF. Compared to diesel, both biodiesels showed significant reduction in smoke opacity, CO emissions and small reduction in HC emissions, while CO_2 emission varied with the type of biodiesel. Due to higher flame temperature, NO_x emissions of the both biodiesels were increased. Advancing the injection timing for biodiesels would increase the premixed combustion phase, peak cylinder pressure and temperature, which resulted in lower smoke opacity, CO and HC emissions but higher NO_x emissions. Retardation of SOI at higher loads can reduce the NO_x emissions. The WPOME produced less smoke, CO, HC emissions and more NO_x emissions than those for COME. Better performance was occurred for WPOME than COME.

Rahman et al.,[15] conducted the experimental investigation to study the effects of idling speed and load on the four cylinder in-line, direct injection CI engine using pure diesel and 5%, 10% and 20% (PB5, JB5, PB10, JB10 and PB20, JB20) of Jatropha and Palm biodiesels blends with diesel. The various properties of both biodiesels were in the range of ASTM D6751. The experiments were performed at two idling conditions 1000 rpm at 10% load and 1200 rpm at 12% load. Jatropha biodiesel had high viscosity, low calorific value and low cetane number compared to palm biodiesel, which resulted in poor spray characteristics and incomplete combustion. Compared to diesel, the CO and HC emissions were reduced for both biodiesels with increase in biodiesel blend ratio. Jatropha blend produced more CO and HC emissions than Palm biodiesel blend. Increasing of idling speed and load conditions would decrease the CO and HC emissions. With respect to diesel, NO_x emissions were highest for palm biodiesel with second highest for Jatropha biodiesel. Increase in idling load and speed would decrease the NO_x emissions due to lower ignition delay. With increase in blend ratio, idling load and speed, the BSFC was increased for biodiesel blends due to lower heating value. Due to more cetane number and high heat release rate, the peak cylinder pressure was higher and occurred earlier BTDC for biodiesel blends than diesel. Increase in cylinder pressure was lower at high idling conditions. Comparisons showed that the PB20 produced lowest CO and HC emissions and highest NO_x emissions at both idling conditions. JB20 and PB20 produced highest in-cylinder pressure and BSFC.

Sahoo and Das,[16] conducted the experiments on single cylinder, air cooled diesel engine (rated power 6 kW) using pure diesel and three biodiesels blends of Jatropha, Karanja and Polanga methyl esters with diesel fuel. Experiments were conducted with pure biodiesels and their blends of 20% and 50% by volume with diesel at engine loads of no load (0%), part load (50%) and full load (100%). The objective of study was to find the effect of different fuels on combustion parameters such as ignition delay, heat release rate, rate of generation of peak pressure. For biodiesels, the peak cylinder pressure was occurred after TDC that reduced the possibility of knocking. Considering the peak cylinder pressure, the neat polanga biodiesel (PB100) was the optimum blend with peak cylinder pressure of 6.61 bars higher than diesel fuel. Compared to diesel, the maximum heat release rate was lower for three biodiesels and their blends due to earlier start of combustion and lower ignition delay. Among biodiesels, JB20 produced highest HRR. Due to shorter ignition delay, the premix combustion phase for biodiesel and its blends was less intense, which resulted in earlier maximum heat release rate as compared to neat diesel. Ignition delays of JB100, PB100 and KB100 were shorter than diesel. Despite of having small number of diglycerides with higher boiling point than diesel, the esters with high molecular weight would be break down during injection of biodiesel into high temperature air. This chemical reaction produced the gases having low molecular weight. Quick gasification of this lighter oil in the edge of the spray spreads out the jet, and thus volatile compounds ignited earlier and the ignition delay period would be reduced.

Sanjid et al.,[17] conducted the experimental investigation on single-cylinder, four-stroke, water cooled, DI diesel engine (rated power 7.7 kW at 2400 rpm) using Palm, Jatropha biodiesel blends and combined Palm-Jatropha biodiesel blends with diesel fuel. Comparisons were done with the base tests conducted with pure diesel. The blends used in this study were 10% and 20% of jatropha and palm biodiesels (JB10, PB10, JB20, PB20), 5% palm and 5% jatropha biodiesel (PBJB5), 10% palm and 10% jatropha biodiesel (PBJB10) with the corresponding percentages of diesel fuel for each blend. Tests data were collected for the speed range of 1400-2400 rpm. The properties various of biodiesel blends were found in the acceptable range of ASTM standard. PBJB5 and PBJB10 biodiesel blends were consisted of slightly high viscosity, density, flash point and low calorific value compared to pure diesel. Compared to PBJB5, the reduction in brake power and increment in BSFC were more for PBJB10 blend. The Brake power of PBJB5 and PBJB10 were lower than PB10 and PB20 respectively, and higher than JB10 and JB20 respectively. The BSFC of PBJB5 and PBJB10 were lower than JB10 and JB20 respectively, and higher than PB10 and PB20 respectively. Due to high viscosity, poor atomization and lower calorific value of biodiesels, the brake power was reduced and the specific fuel consumption was increased. With respect to pure diesel and PBJB10, the CO, HC emissions were higher and NO emissions were lower for PBJB5. The HC, CO emissions of PBJB5 and PBJB10 were slightly lower than JB10 and JB20 respectively, and slightly higher than PB10 and PB20 respectively. The reduction in HC, CO emissions and increase in CO_2 were due to more molecular oxygen content and complete combustion of biodiesel blends. Compared to diesel fuel, the average noise levels were higher for PBJB5 than PBJB10. The reduction in ignition delay period due to high cetane number of biodiesel blends would reduce the peak cylinder pressure, which was resulted into lower noise levels.

D. Rakopoulos et al.,[19] conducted the experiments on six-cylinder, heavy duty, turbocharged, DI 'Mercedes-Benz' bus diesel engine using 10% and 20% (by volume) blends of four vegetable oils sunflower, cottonseed, corn and olive oil with diesel fuel. Comparison of vegetable oils were done with the base tests conducted with pure diesel. The experiments were conducted at three engine loads of 20%, 40% and 60% of full load and at two speeds 1200 rpm and 1500 rpm. Each test was repeated for three times and the mean values were selected. Due to high viscosity and density, low cetane number and calorific value of vegetable oils, the fuel droplet size was large and uniform distribution of fuel would not take place, which resulted in high ignition delay and poor combustion for vegetable oil blends. Compared to diesel, the smoke density was reduced for all vegetable oil blends with increase in blend ratio. Highest smoke reduction was occurred for olive oil blend due to its lower content of linoleic acid, whereas the smoke reduction of cottonseed oil blend was second highest due to high content of palmitic acid. Compared to diesel, the exhaust emissions such as NO_x, CO and HC were increased with the increase in the percentage of vegetable oil in the blend. The NO_x and CO emissions were lower for cottonseed and olive oil blends while the HC emission were lower for sunflower and corn oil blends. The BSFC and BTE of most of the vegetable oil blends were slightly higher than the diesel fuel. BSFC was lowest for sunflower and cottonseed oil blends. With increase in loading conditions, smoke, NO_x, HC emissions and BTE were increased, while CO emissions and BSFC were decreased.

Rahman et al.,[20] conducted experiments on four-cylinder in-line, four-stroke, direct injection diesel engine using 5%, 10% and 20% (PB5, CIB5, PB10, CIB10 and PB20, CIB20) of Palm and Calophyllum inophyllum biodiesels blends with diesel fuel at high idling conditions. The experiments were performed at three engine idling conditions 1000 rpm at 10% load, 1200 rpm at 12% load and 1500 rpm at 15% load. Palm biodiesel had high viscosity, flash point and low calorific value, cetane number compared to Calophyllum inophyllum biodiesel, which resulted into incomplete combustion due to poor atomization. With increase in blend ratio of both biodiesels, the Brake specific energy consumption was increased and brake thermal efficiency was decreased at low idling conditions, while the changes in BSEC and BTE were low at high idling conditions of 1500 rpm 15% load. With increase in idling conditions, the BSEC was increased while the BTE was decreased. Compared to PB20, the CIB20 had higher BTE and lower BSFC. The exhaust gas temperature was decreased with increase in biodiesel blend ratio due to better combustion. The EGT was lowest for CIB20. Compared to diesel, the CO and HC emissions were low for both biodiesels. CO and HC emissions were lowest for CIB20. Increasing of idling speed and load conditions would decrease the CO and HC emissions. With increase in blend ratio of both biodiesels, the NO_x emissions were slightly increased as compared to diesel. PB20 and CIB20 produced highest NO_x emissions. Increase in idling load and speed conditions would decrease the NO_x emissions significantly due to reduction in ignition delay. Calophyllum inophyllum biodiesel produced higher BTE, NO_x and lower BSFC, EGT, CO, HC as compared to palm biodiesel.

Jagannath et al.,[24] conducted the experiments on single cylinder, four-stroke, DI diesel engine (rated power of 3.78 kW at rated speed 1500 rpm) using waste fried oil methyl ester to know the effects of compression ratio, engine load and biodiesel blend ratio on the performance and engine emissions using response surface methodology. The BTE, BSFC, EGT, CO, PM and NO_x were the response parameters. Three levels of compression ratio (14.5, 16.5 and 17.5), three levels of biodiesel blend (B0, B50 and B70) and eight levels of brake load (0.5 kW to 4 kW in the step 0.5 kW) were selected for experiments. Total 72 experiments were conducted. With increase in load, the BTE and EGT were increased, while the BSFC was decreased due to the higher combustion temperature and better atomization at higher loads. With increase in biodiesel blend percentage, BTE was slightly decreased, while the BSFC and EGT were increased due to low volatility, high density and high viscosity of biodiesel. With increase in compression ratio, the EGT and BTE were increased, while the BSFC was decreased. With increase in blend percentage and compression ratio, CO and PM emissions were decreased, while the NO_x emissions were increased. Optimization of experimental results would give the optimum combination for engine performance as B0 blend, brake load of 2.15 kW and CR of 15.8. For the minimum exhaust emissions, the optimum combination was B57 blend, brake load of 3.5 kW and CR of 14.5. Final optimum conditions for engine performance as well as emissions were B30 blend, brake load of 3 kW and CR of 16.5.

2.2 Engine Corrosion and Wear

Corrosion is the chemical or the electrochemical reactions of exposed engine component surface with the various acidic and oxygen components present in the fuel as well as atmosphere. Wear is the mechanical removal of metal from the adjoining surfaces of engine component due to abrasion and relative sliding motion of the engine components.

Dhar and Agarwal,[3] have done experiments on four-cylinder inline, four-stroke, DI diesel engine using 20% Karanja oil methyl ester blend (KOME20) and pure diesel to study the effects on tribological properties of Lubricating oil. The effects of diesel and biodiesel on degradation of lubricating will be different due to differences in their properties. First, they operated the engine with diesel for 200 hours under the loading conditions prescribed by IS: 10,000 (Part IX). Then the engine pistons rings, pistons, cylinder liners, gudgeon pins and lubricating oil were replaced by the newer ones and then the engine was operated using 20/80 KOME/Diesel blend for 200 h at the similar operating conditions of first phase. Lubricating oil samples were extracted from oil sump at every 20 h of running. Compared to diesel, the density of lubricating oil was increased at higher rate for KOME20. Polymerization of lubrication oil, deposition of wear debris and moisture exposure would increase the density. Viscosity of lubricating oil was increased more for KOME20 at 40°C and more for diesel at 100°C due to polymerization of lubricating oil. After 100 h, the reduction in viscosity of lubricating oil was more for KOME20 than diesel due to dilution with fuel. Carbon residues were slightly higher for KOME20 due to deposition of non-combustible part of lubricating oil. KOME20 did not produce harmful effects on copper parts of engine. Due to higher wear debris, the ash content of KOME20 fueled lubricating oil was higher than diesel. After 100 h of operation, the reduction in TBN of KOME20 lubricating oil was higher than diesel due to interaction of corrosion additives with biodiesel. For biodiesel fueled lubricating oil, the deposition of wear debris such as copper, iron, lead, aluminum, chromium and magnesium were higher, while nickel and zinc debris were slightly lower as compared to diesel after 100 h of engine operation.

Patel et al.,[12] conducted the life cycle analysis of two separate similar CI engines as per IS 10000: 1980, in which one engine was fueled with diesel fuel and the other was fueled with B20A4 (20/80 biodiesel/diesel blend with addition of 4% Diethyl ether additive). Before each operation, engine was disassembled and the various physical dimensions of various parts of CI engine were measured and then the engine was again assembled. Preliminary running of 49 hours (7 loading cycles, each with 7 hours of running at various engine loads) at rated speed was carried out. After that engine lubricating oil was replaced by newer one and then the long-term endurance test was carried out, in which the engine was operated for 32 cycles (16 hours of continuous running at various loads for each cycle) at rated speed. After every 128 hours of running, the lubricating oil sample was extracted from oil sump for various tribological inspections such as ferrography, atomic absorption spectroscopy and viscosity. After 512 h long endurance test, the surface roughness of various engine components was measured. The use of B20A4 reduced the wear of various engine components as compared to diesel. The deposition of various metal debris was lower for B20A4 fueled engine's lube oil as compared to lube oil of diesel fueled engine.

Fazal et al.,[21] compared the corrosive behaviour of pure palm biodiesel and petroleum diesel fuel. They conducted the immersion tests, in which the rods of copper, aluminum and stainless steel were immersed separately in both diesel (B0) and palm biodiesel (B100) for 1200 hours at 80°C and continuous stirring was done 250 rpm. The oxidation level with water content, presence of metal species, acid concentration and compositional characteristics of rods were measured. The results showed that biodiesel was more corrosive than diesel due to presence of more oxygen content, free unsaturated fatty acid, and water content. Measurement of loss of weight and average density of pits showed that the corrosion of copper and aluminum was more for exposing in biodiesel than diesel, while the stainless-steel had very less corrosion for both diesel and biodiesel. Compared to as-received conditions of both fuels, there were significant changes occurred in colours of diesel and biodiesel for copper rod exposition, which showed the degradation of fuel composition and fuel properties. The total acid number of biodiesel was significantly increased compared to diesel after exposed to all metal rods. Copper exposed to biodiesel showed highest increase in TAN number. Increment in density and viscosity were less for all metals exposed diesel than those exposed to biodiesel. Density of the copper exposed to biodiesel was crossed the limit provided by ASTM standard as compared to aluminum and stainless steel exposed to diesels and biodiesels, whereas the viscosity of all metal exposed to diesels and biodiesels were within the limit of ASTM standard. Increment of viscosity, density and TAN were degrading the fuel properties. Biodiesel absorbs more water than diesel. The percentage of water content of as-received biodiesels and diesels were almost zero, while for all metal exposed to diesel and biodiesels, the percentage of water content was crossed the ASTM standard. The water content of all metals exposed to diesel was lower than those exposed to biodiesel.

Pandey et al.,[22] conducted experiments on 160 hp, 6 cylinders, four-stroke, turbocharged, direct injection diesel engine using neat karanja biodiesel (B100) and neat diesel (B0). Performance tests were carried out at variable engine speed range of 1200-2400 rpm under full load conditions, while the wear tests were carried out at part loads with speed of 1800 rpm for both fuels. Long term endurance tests consisted of running of engine for 100 hours were carried out for both fuels. After every 10-hour time interval, the lubricating oil was extracted from oil sump to find out the amount of deposition of metal debris in it. The results showed that the brake power was slightly decreased for Karanja biodiesel compared to neat diesel. For karanja biodiesel, 78% reduction in CO emissions, 40% reduction in HC emissions and 10% increment in NO_x emission were occurred as compared to pure diesel fuel. Compared to diesel fuel, the lubricating oil extracted from Karanja biodiesel fueled engine showed 35% reduction in wear debris of metals such as Cu, Al, Cr, Ni, Fe and Pb.

Bora et al.,[23] have done the analysis of wear and tear of single cylinder, air cooled, direct injection diesel ignition engine (rated power 5.9 kW at 1500 rpm) using pure diesel and 20% karanja biodiesel blend (B20K) with diesel fuel. According to the IS: 10000, the long-time endurance tests of 512 hours of engine operation were done on two separate diesel engines, one with B20K blend and other with pure diesel. The lubricating oil used for both tests was SAE grade 15W 40. Each endurance test was consisted of operating the engine for 32 cycles (16 hour of continuous running for each cycle), in which the lubricating oil was extracted from oil sump after every 150 hour of engine operation for various wear tests. Compared to diesel fueled engine, specific fuel consumption was increased, while the smoke opacity was decreased for B20K blend. The reduction in viscosity of lubricating oil was less for B20K blend than that for diesel, which showed that the viscosity of lubricating oil was less affected by B20K blend. The amount of iron debris in the lubricating oil as a result of wear of various components of diesel engine was less for the B20K fueled engine as compared to lube oil from diesel fueled engine.

Sinha and Agarwal,[25] had conducted the long-term endurance tests on two separate four-cylinder, water cooled, direct injection (rated power 41 kW at 3000 rpm) CI engines using neat diesel (B0) and 20% (v/v) rice bran oil methyl ester blend (B20) to study the degradation of lubricating oil and wear of the important components of the engine. Two separate endurance tests were conducted for diesel (B0) and ROME (B20) blend. Each endurance test consisted of ten cycles (10 hours for each cycle means total 100 hours) of continuous running of engine. After every 20 h of engine running, the samples of lubricating oils were drawn from oil sump for wear debris analysis. Before each endurance test for diesel and B20, old cylinder liners, piston rings, bearings, pistons were replaced by newer ones and physical dimensions of them were recorded. The results showed that carbon deposits on cylinder head, piston crown and injector tip were lower for B20 as compared to diesel fuel. Except big end bearing, the lower wear was observed for B20. Weight loss of piston rings was lower for B20, in which it was maximum for second compression ring and minimum for oil control ring. Except Al and Pb, deposition of all other metal debris such as Fe, Ni, Cr, Zn and Mg were lower for B20. Using surface electron microscope and surface profiles at TDC, BDC and midstroke, it was found out that, the cylinder liner wear was less for B20, in which higher wear of cylinder liner was occurred at TDC and antithrust side. More temperature and pressure were generated at TDC location, which resulted in higher wear at TDC location. The antithrust side of cylinder liner was mainly coming in contact during compression, expansion and exhaust stroke of engine operation, which resulted in higher wear of liner.

2.3 Use of Optimization Methods for Engine Experiments

Saravanan et al.,[4] conducted the comparative study of combined effect of the three control parameters on the NO_x emission of crude rice bran oil methyl ester (CRBME) fueled four-stroke, air cooled, DI diesel engine. The control parameters were injection timing were (standard 23.4° CA, 2.5° CA BTDC, 2.5° CA ATDC), exhaust gas recirculation (0%, 10%, 15%) and injection pressure (210 bar, 230 bar, 250 bar). The response variables NO_x emission, smoke density and brake thermal efficiency were measured at no load, part load and full load. Using Taguchi's L_9 orthogonal array, nine different experiments of levels of three control parameters were designed. The comparisons were done with base test conducted with diesel. For smoke density and NO_x emissions, the smaller the better S/N ratios and for brake thermal efficiency, larger the better S/N ratios were selected. Weighting factors of 0.4 (W_1), 0.3 (W_2) and 0.3 (W_3) were assigned to response variables NO_x emissions, smoke density and brake fuel conversion efficiency respectively. ANOVA analysis was carried out to find the contribution of each control parameter on response variables. At no load and part load, the standard injection timing 23.4^o CA, 10% EGR and 220-230 bar injection pressure were optimum combination for CRBME. At full load for CRBME, the optimum combination was standard injection timing 23.4^o CA, 10% EGR and 240-250 bar injection pressure. The contribution of % EGR was more at no load and part load due to lower heat release rate and cylinder temperature, while at full load, the contribution of injection timing was high due to high HRR and temperature. Comparison of test results at optimum combination levels for CRBME and normal condition test with diesel at rated load showed that the ignition delay was longer for CRBME as compared to diesel, which was resulted in lower peak pressure, lower maximum heat release rate and more combustion of fuel after TDC.

Wilson and Udayakumar,[7] have studied the Taguchi method of design of experiments for optimizing the control factors of single cylinder, DI diesel engine for the response variables such as NO_x emissions and economy of fuel (BSFC). They have taken five control factors as area of nozzle-hole, clearance volume, static injection timing (angle), valve opening pressure and load torque with each one having four levels. Full factorial would give no. of experiments as $4^5 = 1024$. Instead of testing one factor at a time (OFAT), simultaneous variation in all factors was carried out by defining Taguchi's L_{16} orthogonal array for reducing the number of experiments. The experiments for these 16 combinations were carried out and from their results, the predicted value of S/N ratio for each factor was calculated. The level of parameter having highest S/N ratio would be selected as optimum parameter. Then the validation of these optimum combination was checked with confirmation experiment. The deviation between actual (from confirmation experiment) and predicted S/N ratio was within 10% for NO_x emissions and only 1.86% for BSFC. The Analysis of Variance (ANOVA) was carried out to know the percentage contribution of each factor in controlling the response variables. The load torque and area of nozzle hole were less effecting on NO_x emissions and BSFC. The injection timing had temperate effect, whereas the valve opening pressure had superior effect on both response variables. The clearance volume had second superior effect on them but it was in the opposite direction. The results show that the Taguchi is very operative and efficient method for finding variations of all control constraints simultaneously on the variables of engine performance.

Win et al.,[8] have done study on application of Taguchi method for optimization of operating and injection system parameters of single cylinder, four-stroke, air cooled, direct injection diesel engine for response variables such as fuel consumption, minimum noise and emissions. Instead of checking one parameter at a time, testing of all parameters simultaneously with minimum number of experiments could be done with Taguchi's orthogonal array. They had selected total eight control factors, out of which two were engine operating parameters such as load and speed and six were injection system parameters such as static fuel timing of injection, opening pressure of nozzle valve, nozzle tip projection, number of nozzle holes, diameter of plunger and diameter of nozzle hole. Each of these parameters were varied at two levels to find effects of on seven response variables such as noise of engine, noise of combustion, BSFC, smoke, HC, NO_x and CO emissions. Based on the degree of freedom of control factors, the number of experiments were reduced to 16 by using L_{16} orthogonal array. Seven two factor interactions among eight control factors were selected. The level of control parameter and two parameter interactions having highest S/N ratio would be selected and then ANOVA analysis was carried out. From this, the optimum combinations of control parameters and their interactions were found out and the confirmation test was carried out for assuring the predicted response obtained from optimum combination. Confirmation test results showed good agreement with predicted responses. Taguchi method would effectively describe the level of significant control parameters along with percentage contribution to average variation of response variables.

S. Saravanan et al.,[11] have done optimization study to know the combined effect of fuel injection timing, percentage of EGR and fuel injection pressure on the NO_x emissions of a diesel fueled diesel engine. The control parameters were injection timing were (standard 23.4^o CA, 2.5^o CA BTDC, 2.5^o CA ATDC), exhaust gas recirculation (0%, 10%, 15%) and injection pressure (200-210 bar, 220-230 bar, 240-250 bar). The response variables were NO_x emission, smoke concentration and brake fuel conversion efficiency. Using Taguchi's L_9 orthogonal array, the number of experiments were reduced from 27 to 9, in which the engine was operated from no load to full load. For the smoke and NO_x emissions smaller the batter and for the brake fuel conversion efficiency larger the better loss functions were considered. Normalized loss function was defined due to differences in measuring units of response variables. The injection pressure was contributing more to reduce NO_x emissions with low smoke opacity. Percentage EGR showed less contribution to response variables for higher weighting factor of smoke concentration. Injection pressure was contributing more for lower weighting factor of NO_x emission. Retarded injection timing would reduce the duration between start of combustion and maximum pressure occurrence, which would cause the reduction in amount of burned gases, peak pressure and peak temperature that resulted in lower NO_x formation. 10% EGR decreased the NO_x emissions but it was increased the smoke opacity due to lower oxygen concentration. Good atomization and high fuel vaporization rate would be achieved with retarded fuel injection which remove the need for higher injection pressure. So, the retarded injection timing 2.5^o CA, 0% EGR and standard injection pressure is the optimum combination for reducing NO_x emission with lower smoke concentration and higher brake fuel conversion efficiency.

2.4 Conclusion from Literature Review

Plant oils and their biodiesels seems to be best alternative for reducing the pollution of fossil fuels from CI engines. Various papers related to use of vegetable oil and biodiesel in CI engine showed that the 100% vegetable oil cannot be used directly in the diesel engine due to high viscosity, density and low volatility compared to diesel. By using transesterification method, the viscosity of vegetable oil can be decreased by converting into biodiesel. Still the biodiesel has slightly high viscosity and density as compared to diesel. Use of biodiesel in CI engine increases the BTE, BSFC, CO_2 and NO_x emissions, while reduces the EGT, PM, CO and HC emissions. Various blends of biodiesels with diesel have been studied by various researchers. According to them, biodiesel can be mixed with diesel fuel up to 20% without any engine modifications. More percentage of biodiesels in the blend causes the poor atomization and incomplete combustion. Wear analysis of CI engine components showed that the biodiesel is less harmful to vital components of the CI engine as compared to diesel. Amount of deposition of wear metal debris in lubrication oil is low for biodiesels. Literature related to Taguchi analysis showed that using this method the number of experiments can substantially reduce which will save time and resources. Also with minimum experiments, it will give the optimum combination at which the values of response variables will be maximum/minimum. Till now most of research is related to use of one biodiesel blend or comparison of two separate biodiesel blends in CI engine. Literature related to use of two biodiesels simultaneously in a single blend is very less available. Also, there is less research available about which biodiesel is most efficient among all available biodiesels. So, the research is required in the area of most promising biodiesels and their optimum percentage blends.

2.5 Problem Definition

From the conclusion of the literature survey, the definition of problem is very simple. For diesel we have one source that is crude oil, but for biodiesel we have many sources. As there are different types of edible and non-edible plant oils available for the biodiesel production, it is necessary to know which plant oils and their resulted biodiesel is best for substituting the diesel. As much of the researchers have done research on the use of single or two separate biodiesel blends in CI engine, our aim is to find out the optimum percentage of best two biodiesels in the single blend at which it will give maximum performance, combustion and minimum emissions. The final result should be a blend of 70% of diesel and 30% of the two optimized biodiesels.

2.6 Objective

1. To compare the performance, combustion and emissions parameters of CI engine fueled with the different biodiesel blends having 25-25% of any two different biodiesels and 50% of diesel at the constant operating parameters such as injection pressure, compression ratio and injection timing obtained from previous experimentation. From this, the best two biodiesels are identified on the basis of engine performance, combustion and emission.

2. For the best two biodiesels, experiments are conducted with the biodiesel blends having 70% diesel and 30% (5-25, 10-20, 15-15, 20-10, 25-5) of two best biodiesels at constant operating conditions. From this, the optimum percentage of best two biodiesels in the single blend is identified.

2.7 Closure

In this chapter, the literature related to use of vegetable oil and biodiesel in CI engine, effects of diesel-biodiesel blends on the engine performance, emissions and wear has been discussed. Also, the literature related to the use of Taguchi method for getting the optimum combination of input engine parameters with minimum number of experiments has been covered. The objective of present study and definition of problem have been discussed. In the third chapter, the engine setup, various exhaust emission measuring instruments, methodology of experimentation, repeatability of experiments and the uncertainty analysis have been discussed.

Chapter 3

Experimental setup and Methodology

This chapter includes the specification of engine setup, the instruments used for various engine emission measurement, experimental procedure, performance, combustion and emission analysis for the optimization of two best biodiesels. Statistical analysis, repeatability of experiments and the uncertainty analysis of various measuring parameters are also included in this chapter.

3.1 Experimental Setup

For fulfilling the objectives of present study mentioned in chapter - 2, the experiments are carried out on the computerized Kirloskar, single cylinder, four-stroke, variable compression ratio, water cooled, DI engine having rated power 3.5 kW at rated speed of 1500 rpm. This engine has dual mode means it can be ran on diesel or petrol. For our study we are using it in diesel mode. Water cooled eddy current dynamometer is used for measuring engine loading, while crank angle encoder sensor is used for measuring engine crank angle. For cooling of engine exhaust gases, the calorimeter is provided. The motor is provided for the continuous supply of water through engine combustion chamber and calorimeter. The flow rate of supply water to engine and calorimeter is measured and controlled by two different rotameters. The fuel tank is equipped with digital piezo sensor and pressure sensor. The K – type thermocouples and RTD type temperature sensors are used for measuring temperatures of water at the inlet and outlet of the engine and calorimeter and also for measuring the temperatures of exhaust gas at the inlet and outlet of the calorimeter. Exhaust gas analyzer is used for measuring the various emissions such as CO, CO_2, O_2, HC and NO_x in the exhaust gases. Exhaust smoke density is measured by smoke meter. For measuring various performance parameters of engine such as BSFC, IP, BP, BMEP, brake thermal efficiency, indicated thermal efficiency, air fuel ratio, volumetric efficiency and mechanical efficiency of the engine at the constant operating parameters of injection pressure, compression ratio and injection timing, the lab-view “Enginesoft” software is used, which gives all the details of engine performance and combustion parameters at each loading condition through the signals received from various sensors. The specifications of the engine test rig available at the institute are shown in table 3.1. The Line diagram of experimental engine setup and the actual engine setup are shown in the figures 3.1 and 3.2 respectively.

Table 3.1: Engine test rig set up Specifications provided by manufacturer

Product	Research engine test setup, single cylinder, four stroke, multi fuel, variable compression ratio single cylinder, code - 240
Engine	Single cylinder, four stroke, water cooled, stroke 110 mm, bore 87.5 mm, capacity 661 cc. Diesel mode: Power 3.5 kW, Speed 1500 rpm, CR range 12:1 to 18:1, Injection variation: 0-25°BTDC
Dynamometer	Eddy current, water cooled, along with loading unit
Propeller shaft	Along with universal joints
Air box	Mild steel fabricated with orifice meter and manometer
Fuel tank	15 liter capacity, Duel compartment with fuel metering pipe of glass
Calorimeter	Type pipe in pipe
Piezo sensor	Combustion: Range 0-345 bar, with low noise cable Diesel line: Range 0-345 bar, with low noise cable
Crank angle sensor	Resolution 1 degree, speed 5500 rpm with TDC pulse
Data acquisition device	NI USB-6210, 16 bit, 250 kS/s.
Digital voltmeter	Range 0-20 V, panel mounted
Temperature sensor	Type RTD, PT100 and K type thermocouple,
Temperature transmitter	Type two wire, Input RTD PT100, Range 0-100 deg C, Output 4-20 mA and Type two wire, Input thermocouple, Range 0-1200 deg C, Output 4-20 mA
Load sensor	Load cell, Type strain gauge, Range 0-50 kg
Fuel flow transmitter	DP transmitter, Range 0-500 mm WC
Air flow transmitter	Pressure transmitter, Range (-) 250 mm WC
Software	“Enginesoft”, engine performance analysis software
Rotameter	Engine cooling 40-400 LPH, Calorimeter 25-250 LPH
Pump	Type Monoblock
Overall dimensions	W 2000 × D 2500 × H 1500 mm

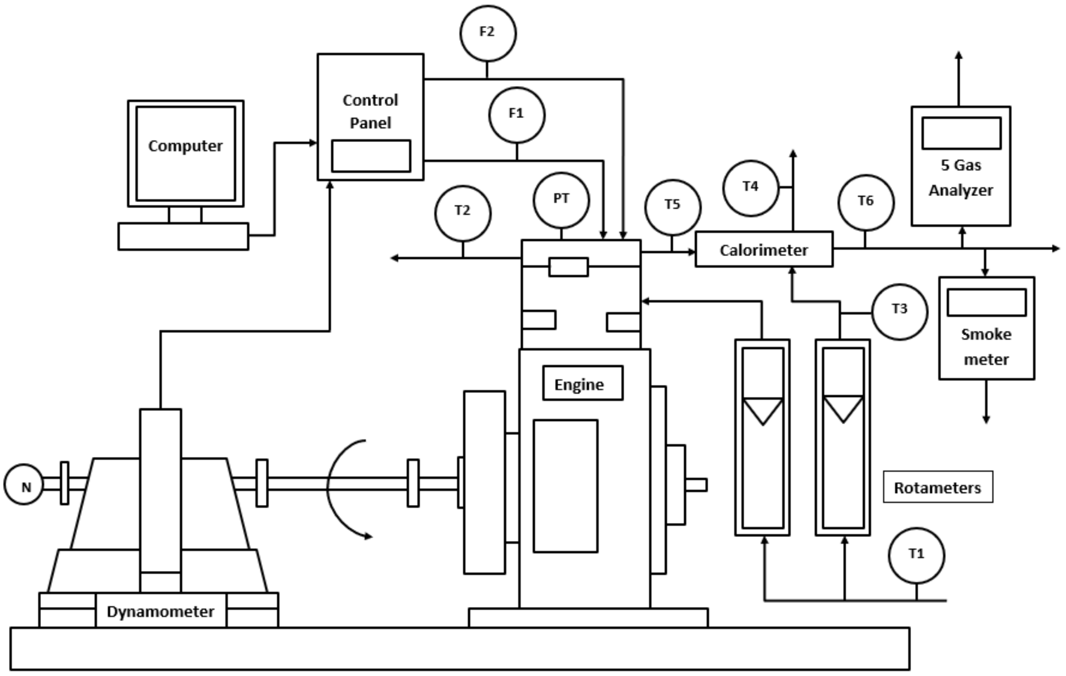

Figure 3.1: Line diagram of engine setup used in study. T1 - Engine water inlet temperature (°C), T2 - Engine water outlet temperature (°C), T3 - Calorimeter water inlet temperature (°C), T4 - Calorimeter water outlet temperature (°C), T5 - Temperature of exhaust gas before calorimeter (°C), T6 - Temperature of exhaust gas after calorimeter (°C), F1 - Fuel consumption measurement unit, F2 - Air flow measurement unit, PT - Pressure transducer, EGA - Exhaust gas analyzer, N - Engine speed measurement. [30]

3.2 Experimental Methodology

For evaluating the two best biodiesels from eight available biodiesels and their optimum percentage in a single blend for CI engine, following methodology is applied. Some methodology is according to full factorial method to reduce the number of experiments and to increase the confidence level.

3.3 Engine Tests

According to literature, the biodiesel can substitute the diesel by up to 20% with less effects on performance and engine wear. We are going to substitute the diesel by 30% of two best biodiesels. We have selected the eight different biodiesels based on the availability of them around the city. These biodiesels are Jatropha, Karanja, Linseed, Rapeseed, Palm, Canola, Neem and Castor. From these, we have to find the best two biodiesels along with their optimum percentage in a single blend. We are conducting the two sets of experiments. In first set of experiments, we are performing 28 experiments for finding two best biodiesels at engine full load. Here, we are keeping the percentage of two biodiesels in the blend as 50%. In the second phase of experiments, we are performing the 5 experiments for finding the optimum percentage of two best biodiesels for no load to full load. Here, we are keeping the percentage of two biodiesels as 30%. As we are increasing the percentage of biodiesels in the blend beyond 20%, it will be interesting to find its effects on engine performance, combustion and emission parameters. All the experiments have similar operating conditions and experimental methodology.

Figure 3.2: Actual experimental engine setup available at the institute

3.3.1 Selection of Best Two Biodiesels

From eight available biodiesels, our aim is to find out the optimum percentage of two best biodiesels in a single blend. For that, we have to find the number of experiments to be conducted. First our aim is to find out which two biodiesels are best for blending with diesel. For this, we are mixing the 25-25% of any two biodiesels with 50% mineral diesel fuel. Our assumptions are that, we are mixing only two biodiesels with diesel at a time for any biodiesel blend. The percentage of each biodiesel in each blend is only 25%, while the percentage of diesel fuel in each blend is only 50%. The selection of biodiesel is done randomly. The engine operating parameters such as compression ratio, injection pressure and injection timing are remained as 18, 220 bar and 20^o BTDC respectively for each of these experiments as concerned by Sajan Chourasia[30]. Here we are substituting the 50% diesel fuel with 25-25% of two different biodiesels only for finding the two best biodiesels in terms of engine performance, combustion and emission. It has nothing to do with the optimum percentage of each biodiesel. For providing the same input parameters to all biodiesels, we are keeping its percentage as 25-25%. Here, we are finding the behaviour of each biodiesel with remaining seven biodiesels. As per the combination relation for eight available biodiesels and two biodiesels in each blend, the number of experiments requires to be carried out for optimizing two best biodiesels are $^8C_2 = 28$ in the first set, in which each of biodiesel is mixing with remaining all seven biodiesels. The matrix for evaluating the best two biodiesels from eight different biodiesels is showed in table 3.2.

Table 3.2: Matrix for evaluating the best two biodiesels from available eight biodiesels, where diesel percentage is always 50%, '1' means blending and '0' means no blending

Diesel (50%)	Jatropha (25%)	Karanja (25%)	Palm (25%)	Rapeseed (25%)	Linseed (25%)	Canola (25%)	Neem (25%)	Castor (25%)
Jatropha (25%)	0	1	1	1	1	1	1	1
Karanja (25%)	0	0	1	1	1	1	1	1
Palm (25%)	0	0	0	1	1	1	1	1
Rapeseed (25%)	0	0	0	0	1	1	1	1
Linseed (25%)	0	0	0	0	0	1	1	1
Canola (25%)	0	0	0	0	0	0	1	1
Neem (25%)	0	0	0	0	0	0	0	1
Castor (25%)	0	0	0	0	0	0	0	0

Table 3.3 shows the properties of eight biodiesels available at the institute according to the certain research papers. These properties may vary from paper to paper due to certain reasons such as the type chemical process used for producing methyl esters, the process used to clean the raw methyl esters, type of storage, type of skill and analytical methods used for finding properties.

Table 3.3: Properties of diesel and eight biodiesels available at institute [18, 28]

Property	Diesel	Jatropha	Karanja	Palm	Rapeseed	Linseed	Canola	Neem	Castor
Density @15°C (kg/m^3)	850	879.5	931	864.42	882	874	883	868	961
Viscosity @40°C (cSt)	2.6	4.8	6.13	4.5	4.439	3.752	4.42	5.213	
Cetane number	40-55	51.6	55	54.6	54.4	52	53.7	48	42.3
Calorific Value (MJ/kg)	42-46	39.23	43.42	37.5	37	37.2	38.9	39.81	37.4
Acid value (mg KOH/g)	0.062	0.4	0.42	0.24	0.5	0.058	0.01	0.649	
Flash point (°C)	60-80	135	95	135	170	196	153	76	145
Cloud point (°C)	-20	2.7	7	16	-3.3	-3.8	-2	9	

3.3.2 Selection of Optimum Percentage of Two Best Biodiesels

After identifying the two best biodiesels, the next task is to find the optimum percentage of these two best biodiesels. Though we have used the 50% of two different biodiesels in first set of experiments, our aim was only to find two best biodiesels, not their percentage. Here in second stage, our aim is to find the optimum percentage of two best biodiesels. We are conducting the five experiments for five different diesel/biodiesel blends, in which each blend contains 70% diesel and 30% of two best biodiesels. The percentage of two best biodiesels in these five experiments are 5%-25%, 10%-20%, 15%-15%, 20%-10% and 25%-5% respectively. The engine operating conditions are same as compression ratio of 18, injection pressure of 220 bar, injection angle of 20°BTDC. The results of these experiments are compared with the test conducted with 100% diesel. The final result is a blend of 70% diesel and 30% of two optimized biodiesels. Table 3.4 shows the matrix for finding the optimum percentage of two best biodiesels.

Table 3.4: Matrix for evaluating the optimum percentage of two best biodiesels

% of Optimum Biodiesel 1	% of Optimum Biodiesel 2	% of Diesel	Total %
25	5	70	100
20	10	70	100
15	15	70	100
10	20	70	100
5	25	70	100

3.4 Performance Analysis

Performance means for the given quantity of fuel; how much maximum energy can be extracted by engine and make it available at the crank shaft for the end use. Performance is depending on engine type, engine fuel, operating parameters, type of use and environmental conditions. The performance of the engine is degrading with the time of use due to various carbon and metal debris depositions on critical components, corrosion and abrasion of important components of engine. Here the performance analysis is carried out, first for finding best two biodiesels at same engine operating conditions and then it is carried out for finding optimum percentage of two best biodiesels in a single blend. The engine setup is equipped online fuel measuring meters and various sensors. During performance tests, the mass flow rate of fuel, IP, BP, BTE, BSFC, BMEP, BSEC, mechanical efficiency are directly calculated by “Enginesoft” software given by Apex Innovations. In performance analysis, we want the fuel consumption to be minimum, while the BP, BTE and BMEP to be maximum. Performance readings are taken three times during each experiment for avoiding errors of engine operation, software calculations and atmospheric conditions and also for increasing the confidence level.

3.5 Combustion Analysis

During the combustion of fuel our main concern is to know the ignition delay period, rate of pressure rise, the rate of heat release and occurrence of peak pressure. Lower ignition delay, smoother rate of pressure rise and higher peak pressure are the suitable conditions for efficient combustion of the fuel. With the help of cylinder pressure and crank angle of combustion cycle, the heat release rate (Q_R)and the rate of pressure rise are calculated. To reduce the effect of shocks generated during the experiment, two times smoothing of the pressure values are done. According to the first law of thermodynamics for an open system,

$$\text{Heat release rate} = \text{Net heat release rate} + \text{Rate of heat transfer to the cylinder walls}$$

$$Q_R = \frac{dQ_n}{d\theta} + \frac{dQ_{ht}}{d\theta} \tag{3.1}$$

According to first law of thermodynamics,

Net heat release = Change of internal energy during combustion + Work done

$$dQ_n = dE + dW \tag{3.2}$$

$$dQ_n = C_v dT + PdV$$

Dividing the above equation by $d\theta$,

$$\frac{dQ_n}{d\theta} = C_v \frac{dT}{d\theta} + P\frac{dV}{d\theta}$$

According to ideal gas assumption, $C_v = \frac{R}{\gamma - 1}$ and $PV = RT$, Where R = Characteristic gas constant, $\gamma = \frac{C_p}{C_v}$ is the ratio of specific heats.

$$\frac{dQ_n}{d\theta} = \frac{R}{\gamma - 1}\left(\frac{dT}{d\theta}\right) + P\frac{dV}{d\theta}$$

$$\frac{dQ_n}{d\theta} = \left(\frac{PdV + VdP}{d\theta}\right)\frac{1}{\gamma - 1} + P\frac{dV}{d\theta}$$

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma - 1}\left(P\frac{dV}{d\theta}\right) + \frac{1}{\gamma - 1}\left(V\frac{dP}{d\theta}\right) \tag{3.3}$$

The instantaneous cylinder volume V and rate of change of volume $\frac{dV}{d\theta}$ as mentioned in 3.3 are calculated as:

$$V = V_c + A \times r\left[1 - \cos\left(\frac{\pi\theta}{180}\right) + \frac{1}{\lambda}\left\{1 - \sqrt{1 - \lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)}\right\}\right] \tag{3.4}$$

$$\frac{dV}{d\theta} = \left(\frac{\pi A}{180}\right) \times r \left\{ \sin\left(\frac{\pi\theta}{180}\right) + \frac{\lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)}{2 \times \sqrt{1 - \lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)}} \right\} \tag{3.5}$$

Where, $\lambda = l/r$, $A = \frac{\pi D^2}{4}$, r = crank radius, l = length of connecting rod, D = Diameter of cylinder bore, V_c = clearance volume.

Heat transfer rate to the cylinder wall as mentioned in 3.1 is calculated as:

$$\frac{dQ_{ht}}{d\theta} = hA_\theta \left(T - T_{wall}\right) \tag{3.6}$$

Where T is the mean gas temperature in K, obtained from the ideal gas equation $PV = mRT$, T_{wall} is the mean temperature of cylinder wall in K and h is the heat transfer coefficient in W/m^2K. The instantaneous heat transfer area of the combustion chamber A_θ in $m^2$is given as:

$$A_\theta = A \times \left(1 + \frac{4l_\theta}{D}\right) \tag{3.7}$$

l_θ is the instantaneous in cylinder length that given as: $l_\theta = V/A$. The heat transfer coefficient (h) in 3.6 is calculate from Hohenberg's correlation (Hohenberg, 1979, Zeng and Assanis, 1989)[32],

$$h = 3.26P^{0.8}T^{-0.4}V^{-0.06}\left(S_p + c\right)^{0.8} \tag{3.8}$$

c is the calibration constant that should be 1.4 according to Hohenberg and S_p is the mean piston speed that calculated as: $S_p = 2l_\theta N/60$ in m/s.

Above equations are solved at each crank angle during an experiment using a computer program that gives the accurate values of net heat release rate, rate of pressure rise, cumulative heat release and the pressure-crank angle. The cylinder pressure values and their corresponding crank angle values are input values to this computer program. From the graphs of net heat release rate and pressure-crank angle, the ignition delay and peak pressure are calculated.

3.6 Emission Analysis

Due to incomplete combustion of fuel, the engine exhaust produces HC and CO emissions. Complete combustion of fuel produces CO_2emissions. Higher flame temperature of fuel combustion and concentration of oxygen in the combustion chamber produces NO_x emissions. These gases are very harmful to human life as well as environment. Degradation of environment, depletion of ozone layer and enhancement of global warming forces the government to issue strict guidelines and protocols against the exhaust emission of vehicles. Automobile companies are modifying their engines at regular intervals to meet the strict regulations of exhaust emissions. Here also, the emissions of engine combustion are measured first for finding best two biodiesels and then for finding the optimum percentage of two best biodiesels in a single blend. We want all the exhaust gases and smoke opacity to be minimum. The five gas analyzer manufactured by 'i3sys' company is used for measuring five exhaust gases such as CO, CO_2, HC, NO_x, and O_2. The measurement of CO_2, CO and HC are done by Non-dispersive infrared sensor, while the measurement of O_2 and NO_x are done by electrochemical sensors. For the measurement of gas amount in exhaust gases emission, one end of the tube is connected to five gas analyzer and the other end of tube is inserted into the exhaust pipe for 1-2 minutes at the time of taking reading. The amount of gases in exhaust is shown on the LED panel of five gas analyzer. Smoke contained in the exhaust gas is measured by the smoke meter manufactured by 'i3sys' company. For measuring the smoke, the one end of the hose is connected to smoke inlet of smoke meter, while the other end of the hose is inserted into the exhaust pipe for 2-3 minutes at the time of taking reading. Three readings are taken for five gases as well as smoke to increase the confidence level.

Table 3.5: Measurement range of the exhaust gases measured by five gas analyzer

Sr No.	Exhaust emission parameters	Measurement range
1	Carbon Dioxide (CO_2)	0-20% (volume)
2	Carbon Monoxide (CO)	0-15% (volume)
3	Oxygen (O_2)	0-25% (volume)
4	Nitrogen Oxide (NO_x)	0-5000 ppm
5	Unburned Hydrocarbons	0-20000 ppm

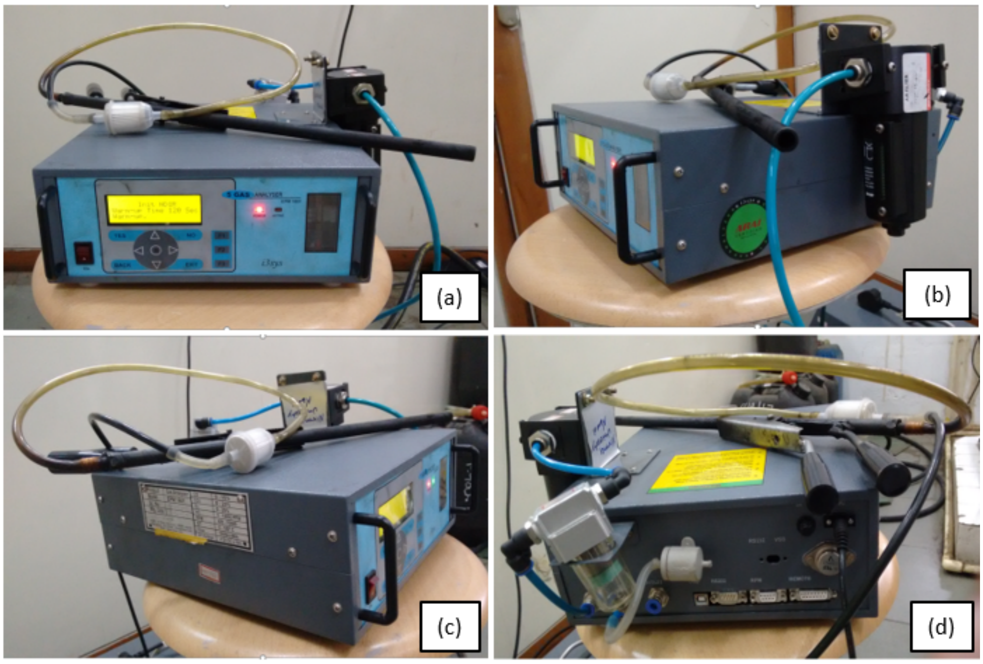

Figure 3.3: Different views of five gas analyzer (a) Front portion (b) Left hand side portion (c) Right hand side portion (d) Rear portion

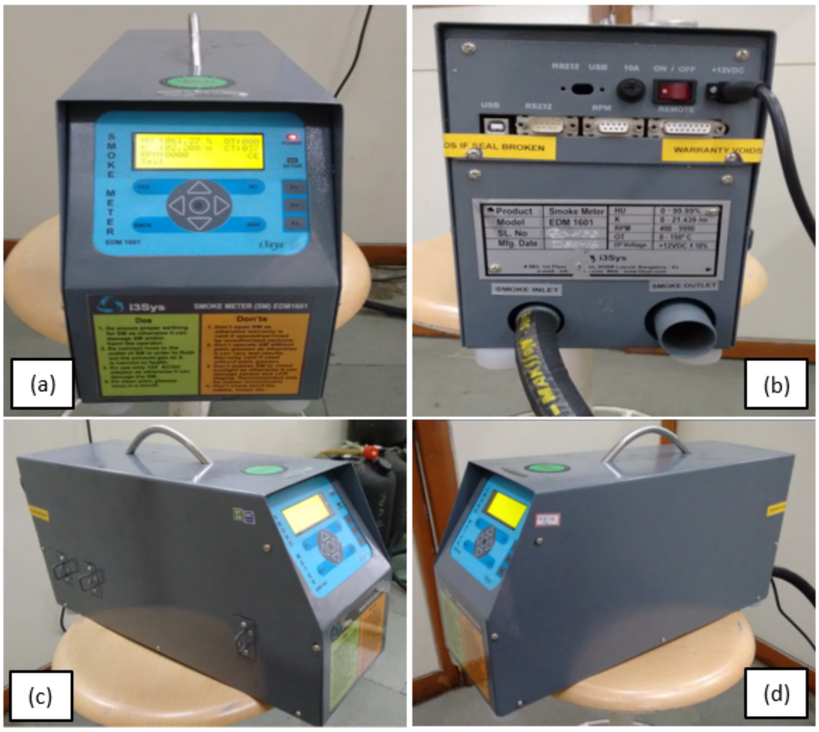

Figure 3.4: Different views of smoke meter (a) Front portion (b) Rear portion (c) Right hand side portion (d) Left hand side portion

3.7 Experimental Procedure

Before starting first experiment, the engine setup is checked with trial run on diesel, whether all the components are working correctly or not. Working of smoke meter and five gas analyzer is also checked. After correct running of all the components, the engine is set to start the experiment. First the diesel/biodiesel blend is made with correct volume measurement of diesel and biodiesels. Then this blend is filled in to the engine fuel tank. The water pump is started and remained ON during whole experiment. The engine is started and the water flow rate to the engine and calorimeter are being set as per the requirement. The engine is allowed to run at no load for 30 minutes for warming up the engine and using the fuel remained in hoses at the end of previous experiments. After that, first reading is taken at 0 kg (no load) load through the lab-view “Enginesoft” software. For increasing the confidence level and avoiding the errors of human errors and environmental conditions, three readings are taken at no load and successive loads at the interval of 10 minutes. After this, the load is increased from no load to 3 kg (25%) load and engine is allowed to run for 15 minutes. After that first reading is taken at 3 kg load and the successive two readings are taken at interval of 10 minutes. Similarly, we are taking the readings of engine performance and emission at 6 kg (50%),9 kg (75%), 12 kg (100%) and 13.2 kg (110%) load conditions. The readings at each load will be taken after the occurrence of steady state condition of the cylinder combustion. For emission measurement, the hose of five gas analyzer is inserted in to the engine exhaust and after occurring the steady state in gas measurement, the readings of CO, CO_2, HC, NO_x and O_2 are taken. Similar procedure is followed for smoke density measurement through smoke meter. Three readings are taken for five gases and smoke opacity for increasing the confidence level. The average of these three readings are taken as final readings. This procedure is followed for each of the experiments being conducted for different diesel/biodiesel blends.

3.8 Repeatability of Experiment

To reduce the effect of engine error, human error, and environmental conditions on the performance and emission results of CI engine, the experiments were repeated for several times to increase the confidence level. Repeatability of experiments is stated in IS 10000 Part IV, which describes the guidelines for declaring fuel consumption, power, efficiency, consumption of lubricating oil and relative correction factors, which will be required to adjust the observed readings with standard reference conditions, as specified in IS 10000 (Part II).

According to Indian standard, the standard reference conditions for constant speed as well as variable speed engines are:

Mean barometric reference pressure, $P_r = 100$ kPa (750 mm of Hg)
Mean reference temperature of air at inlet, $T_r = 300$K (27°C)
Reference relative humidity, $\Phi_r = 0.6$ at 300 K
Rated power is the power declared by manufacturer, which will be delivered by engine under standard reference operating conditions.
Power adjustment factor 'α' - It is the fraction of the output power under ambient local conditions to the power output under standard reference conditions.

$$P_x = \alpha \cdot P_r \tag{3.9}$$

$$\alpha = k - 0.7\,(1 - k)\left(\frac{1}{\eta_m} - 1\right) \tag{3.10}$$

$$k = \left(\frac{P_s - \alpha \cdot \varPhi_x \cdot P_{sx}}{P_r - \alpha \cdot \varPhi_r \cdot P_{sr}}\right)^m x \left(\frac{T_r}{T_x}\right)^n \tag{3.11}$$

Where,P = Brake power, kW;
k = Ratio of indicated power;
P_s= Saturation vapour pressure, kPa;
$\varPhi$ = Relative humidity;
T = Absolute air intake temperature, K;
Subscript$'r'$ corresponds standard reference conditions and subscript 'x' corresponds to ambient local conditions.
Specific fuel consumption adjustment factor $'\beta'$ - It is the fraction of specific fuel consumption under ambient site conditions to the specific fuel consumption under standard reference conditions.

$$\beta = \frac{(BSFC)_x}{(BSFC)_r} \tag{3.12}$$

$$\beta = \frac{k}{\alpha} \tag{3.13}$$

The specific fuel consumption and power adjustment factor β and αwere calculated using Appendices A, B, C, D of IS: 10000 part IV.

3.9 Statistical Analysis

For 28 experiments of finding optimum two biodiesels and then the subsequent experiments of finding the optimum percentage of two biodiesel in a single blend, each experiment was repeated three times to conduct the statistical analysis at 95% confidence level. Following procedure was adopted:

- The mean (x_m), deviation $\mid d_i \mid$and standard deviation (S)of the results at different load were calculated using,

$$x_m = \frac{1}{n} \sum x_i \tag{3.14}$$

$$S = \left[\frac{1}{n} \sum (x_i - x_m)^2 \right]^{\frac{1}{2}} \tag{3.15}$$

$$\mid d_i \mid = \mid x_i - x_m \mid \tag{3.16}$$

- Chauvenet's criterion was applied to eliminate dubious data points; the deviation of the individual points was then compared with the standard deviation in accordance with the information in table E2 of Appendix E, and the dubious points were eliminated. For the final data, present a new mean and standard deviation were computed with the dubious points eliminated from the calculation.

- The confidence interval was estimated by Student's t – distribution of Appendix F.

$$\triangle = \frac{t_s S}{\sqrt{n}} \tag{3.17}$$

$\triangle$= Confidence interval

t = Random variable; values of the same given in the table on Appendix F at different degree of freedom, $\upsilon = n - 1$, where n = number of observations.

- The mean value of emissions and engine parameters of different biodiesel blends were compared with base diesel fuel.

3.10 Uncertainty Analysis

The Uncertainty of measurement is estimated using the procedure given by J P Holman [31]. The uncertainty in measurement is defined as

$$\omega = \sqrt{\left(\frac{\partial R}{\partial V_1}\omega_1\right)^2 + \left(\frac{\partial R}{\partial V_2}\omega_2\right)^2 + ... + \left(\frac{\partial R}{\partial V_n}\omega_n\right)^2} \tag{3.18}$$

R is the result, whose uncertainty is to be estimated. ω_R is the uncertainty in the result. $V_1(i = 1 \text{ to } n)$ are the variables of which R is a function.

Defining the Uncertainty in the percentage, the above equation modifies to

$$\frac{\omega_R}{R} = \frac{1}{R}\sqrt{\left(\frac{\partial R}{\partial V_1}\omega_1\right)^2 + \left(\frac{\partial R}{\partial V_2}\omega_2\right)^2 + ... + \left(\frac{\partial R}{\partial V_n}\omega_n\right)^2} \times 100\% \tag{3.19}$$

The uncertainties in the measurement were estimated from the resolution of the instrument or they were provided from the manufacturer.

The uncertainty in the temperature measurement by thermocouple, $\omega_T = \pm 0.1^0 C$

The uncertainty in the voltage measurement by voltmeter, $\omega_V = \pm 0.1 volt$

The uncertainty in the crank angle measurement by crank angle encoder, $\omega_\vartheta = \pm 0.1^0$

The uncertainty in the time measurement , $\omega_t = \pm 0.1 sec$

The uncertainty in the volume ow measurement, $\omega_m = \pm 1 ml$

The uncertainty in the load measurement by load cell, $\omega_L = \pm 0.25\%$

The uncertainty in the weight measurement by Weighing machine, $\omega_W = \pm 1 mg$

The uncertainty in the exhaust measurement by five gas analyzer, $\omega_g = \pm 0.01 Vol\% / \pm 1 ppm$

The uncertainty in the pressure measurement by piezo sensor, $\omega_p = \pm 0.1 bar$

3.11 Closure

In this chapter, we have discussed the experimental engine setup, analysis of performance, emission and combustion tests, the experimental procedure, repeatability of experiment and the uncertainty analysis of results. In the fourth chapter, the results of first and second phase of experiments have been discussed. Also, the application of Topsis and Promethee methods for assigning the ranking to the different biodiesel blends have been discussed in the fourth chapter.

Chapter 4

Results and Discussion

This chapter consists the results of the experiments and their analysis using Topsis and Promethee methods for finding the optimum percentage of best two biodiesels in a single blend on the basis of engine performance, combustion and emission.

4.1 Test Fuel Properties

Table 4.1: Density and calorific values (tested by bomb calorimeter) of test fuels i.e. diesel, eight biodiesels and their blends

Fuel	Density kg/m^3	Calorific value kJ/kg	Fuel	Density kg/m^3	Calorific value kJ/kg
Diesel	836	43000	Karanja-Castor	877	39817.5
Canola	880	39490	Karanja-Rapeseed	860.5	40242.5
Karanja	880	37270	Karanja-Jatropha	851.75	40681.25
Palm	918	37500	Palm-Neem	877.25	39675
Neem	919	35200	Palm-Linseed	879.75	40701.75
Linseed	929	39307	Palm-Castor	886.5	39875
Castor	956	36000	Palm-Rapeseed	870	40300
Rapeseed	890	37700	Palm-Jatropha	861.25	40738.75
Jatropha	855	39455	Neem-Linseed	880	40126.75
Canola-Karanja	858	40690	Neem-Castor	886.75	39300
Canola-Palm	867.5	40747.5	Neem-Rapeseed	870.25	39725
Canola-Neem	867.75	40172.5	Neem-Jatropha	861.5	40163.75
Canola-Linseed	870.25	41199.25	Linseed-Castor	889.25	40326.75
Canola-Castor	877	40372.5	Linseed-Rapeseed	872.75	40751.75
Canola-Rapeseed	860.5	40797.5	Linseed-Jatropha	864	41190.5
Canola-Jatropha	851.75	41236.25	Castor-Rapeseed	879.5	39925
Karanja-Palm	867.5	40192.5	Castor-Jatropha	870.75	40363.75
Karanja-Neem	867.75	39617.5	Rapeseed-Jatropha	854.25	40788.75
Karanja-Linseed	870.25	40644.25			

In our experimental study, we are using the eight different biodiesels. The selection of these biodiesels is done based on the availability of them around the city area. From the results of experiments, the calculation of various performance parameters such as brake power, mass of fuel consumed, brake specific fuel consumption, brake thermal efficiency require the density and calorific values of diesel, eight biodiesels and their different diesel/biodiesel blends. So, the hydrometer and bomb calorimeter is used for measuring the density and calorific values, respectively for different blends according to the ASTM standard. The properties of diesel, eight biodiesels and their different blends are shown in table 4.1.

4.2 Planning of Experiment

We know that in four stroke diesel combustion, one cycle is completing on the two revolutions of crank shaft means the 720 degrees of crank rotation. The "Enginesoft" software is taking the readings of the engine combustion for 10 cycles means total 7200 degrees rotation of crank shaft. From the "Enginesoft", we are getting the values of engine speed, engine load, crank angle, cylinder pressure and diesel pressure. These values are given as a input in the computer program and from the program, we are getting the values of indicated power, brake power, brake thermal efficiency, peak pressure, occurrence of peak pressure and brake power. We are performing the two sets of experiments. In the first phase, we are performing the 28 experiments for finding the best two biodiesels from eight available biodiesels. In the second phase, we are performing the 5 experiments for finding the optimum percentage of two best biodiesels in the single blend. The results of these 5 experiments are compared with the experiment conducted on the same engine using 100% diesel. As discussed in the section 3.8, each reading is taken three times and their average value is taken as final for increasing the confidence level. As it is difficult to show the names of all the first phase 28 diesel/biodiesel blends in the graphs, following notations are used for the plots as well as calculation of 28 different diesel/biodiesel experiments.

Table 4.2: Notations used for diesel/biodiesel blends for the plots of first phase-28 experiments

Notation no.	Biodiesel blend	Notation no.	Biodiesel blend
1	Canola-Karanja	15	Palm-Linseed
2	Canola-Palm	16	Palm-Castor
3	Canola-Neem	17	Palm-Rapeseed
4	Canola-Linseed	18	Palm-Jatropha
5	Canola-Castor	19	Neem-Linseed
6	Canola-Rapeseed	20	Neem-Castor
7	Canola-Jatropha	21	Neem-Rapeseed
8	Karanja-Palm	22	Neem-Jatropha
9	Karanja-Neem	23	Linseed-Castor
10	Karanja-Linseed	24	Linseed-Rapeseed
11	Karanja-Castor	25	Linseed-Jatropha
12	Karanja-Rapeseed	26	Castor-Rapeseed
13	Karanja-Jatropha	27	Castor-Jatropha
14	Palm-Neem	28	Rapeseed-Jatropha

4.3 Engine Performance, Combustion and Emission Analysis of First Phase-28 Experiments

The engine readings obtained through “Enginesoft” software are taken as a input in computer program and from that the various performance, combustion and emission parameters are found out. From the values of brake power , fuel flow rate and calorific value, the brake specific fuel consumption (BSFC) and brake thermal efficiency (BTHE) are found out. From the graphs of net heat release and pressure-crank angle, the Ignition delay period and the peak pressure are found out respectively. The readings of $NO_x$and HC are taken from five gas analyzer, whereas the readings of smoke are taken from smoke meter. Note that the optimization of best two biodiesels is done on the basis of engine performance, combustion and emission measurement at full load (12 kg) engine operation. So, we are calculating all the necessary values at full load engine operation condition. Table 4.3 shows the results of performance, combustion and emission of 28 experiments performed on engine at full load condition. For the selection of best two biodiesels, we are taking total seven attributes, in which two are performance attributes as BSFC and BTHE, two are combustion attributes as Peak pressure and Ignition delay period and three are emission attributes as NO_x, HC and Smoke density. Each of these attributes have different measuring units. Also, the level of satisfaction of each attribute is different. For the efficient combustion of the fuel, the BSFC and the Ignition delay should be lower, while the BTHE and the Peak pressure should be high. All the lower exhaust emission provides the efficient fuel combustion. Figure 4.1 shows the plots of BSFC, BTHE, Peak pressure and Ignition delay. Figure 4.2 shows the plots of NO_x, HC and smoke density.

Now, from the table 4.3 and figures 4.1, 4.2, we can see that the Neem-Linseed has the lowest value of BSFC, while Neem-Jatropha has the highest value of BSFC. Neem-Linseed has the highest value of BTHE, while the Linseed-Rapeseed has the lowest value of BTHE. The highest and lowest value of Peak pressure are for Canola-Palm and Palm-Linseed, respectively. The lowest and highest value of Ignition delay period are for Rapeseed-Jatropha and Karanja-Palm, respectively. The lowest and highest value of NO_x emissions are for Linseed-Rapeseed and Canola-Neem, respectively. The lowest and highest value of HC emissions are for Karanja-Palm and Linseed-Rapeseed, respectively. The lowest and highest value of smoke density are for Neem-Linseed and Linseed-Castor, respectively. So, we can see that there is no biodiesel blend in our 28 different blends, which has lowest value of BSFC, Ignition delay, NO_x, HC, smoke and the highest value of BTHE and Peak pressure. We have to find the best two biodiesels that can satisfy the given objectives of seven attributes more effectively compared to remaining 26 biodiesel blends. For that we have to assign the relative weightage to the given seven attributes. As we are more concerning on the reduction of exhaust emission of biodiesel blends compared to increase of performance and combustion, we are giving more weightage to the emission attributes. The weightage of 0.25 is assigned to performance attributes (0.125 to both BSFC and BTHE), 0.25 is assigned to the combustion attributes (0.125 to both Peak pressure and Ignition delay) and 0.5 is assigned to the emission attributes (0.166667 to NO_x, HC and smoke). As our problem consists of multiple attributes, we have to use the multi attribute decision making (MADM) techniques for optimization. There are various optimization methods available for MADM, but for our case we are selecting the two optimization methods Topsis and Promethee. The selection of these two methods is done due to their easiness of calculating the solution. Two optimization methods are selected due to the reason that the ranks associated with one method can be different from the ranks associated with other method. In such cases, spearman's rank correlation coefficient is used for finding the closeness of the ranks associated with two methods.

Table 4.3: Performance, combustion and emission results of first phase- 28 experiments at full load engine operation for Topsis and Promethee method

Weightage	0.125	0.125	0.125	0.125	0.16667	0.16667	0.16667
Higher/Lower	Lower	Higher	Higher	Lower	Lower	Lower	Lower
Attributes	BSFC	BTHE	Peak Pr	I Delay	NO_x	HC	Smoke
Biodiesel blend	kg/kWh	%	Bar	Degree	ppm	ppm	%
1	0.285	31.05	58.55	13.458	542	2	2.93
2	0.281	31.43	59.16	9.201	580.33	1.33	3.2
3	0.265	33.76	58.26	13.408	606.67	2	4.27
4	0.277	31.57	59.14	13.952	424	2.33	4.7
5	0.261	34.15	58.82	14.013	422.33	3.67	6.13
6	0.303	29.14	57.04	11.873	390	2	3.5
7	0.306	28.56	56.43	11.283	388.67	2.33	4.03
8	0.305	29.40	56.34	14.968	377.67	1	2.8
9	0.276	32.89	55.38	13.466	324	3	5.13
10	0.283	31.32	56.35	10.925	350.33	3.67	3.7
11	0.281	32.18	57.16	7.583	319.33	2.33	5.13
12	0.292	30.61	54.89	9.425	286.33	3	1.18
13	0.293	30.24	56.35	11.433	271.33	2	3.22
14	0.287	31.59	54.74	8.7	247	5	5.32
15	0.278	31.79	53.40	12.013	319	3.33	4.04
16	0.282	32.03	56.17	10.175	314.67	2.67	6.44
17	0.277	32.26	55.67	9.038	318	4	3.57
18	0.276	31.99	56.40	12.607	365	1.67	3.61
19	0.261	34.40	58.33	8.756	404.33	2	0.95
20	0.273	33.53	57.04	7	374.67	3.33	2.71
21	0.284	31.95	56.80	9.646	335	3	3.21
22	0.315	28.44	54.92	10.094	301	15	3.10
23	0.302	29.55	56.08	11	227.33	9	9.15
24	0.314	28.13	54.20	10.121	167.33	19.67	4.83
25	0.270	32.34	57.88	5.677	388	7.67	2.69
26	0.269	33.56	57.67	12	346.33	3.67	2.35
27	0.265	33.64	58.95	10	324.67	1.33	2.17
28	0.299	29.43	56.03	5.356	331.67	3.67	2.99

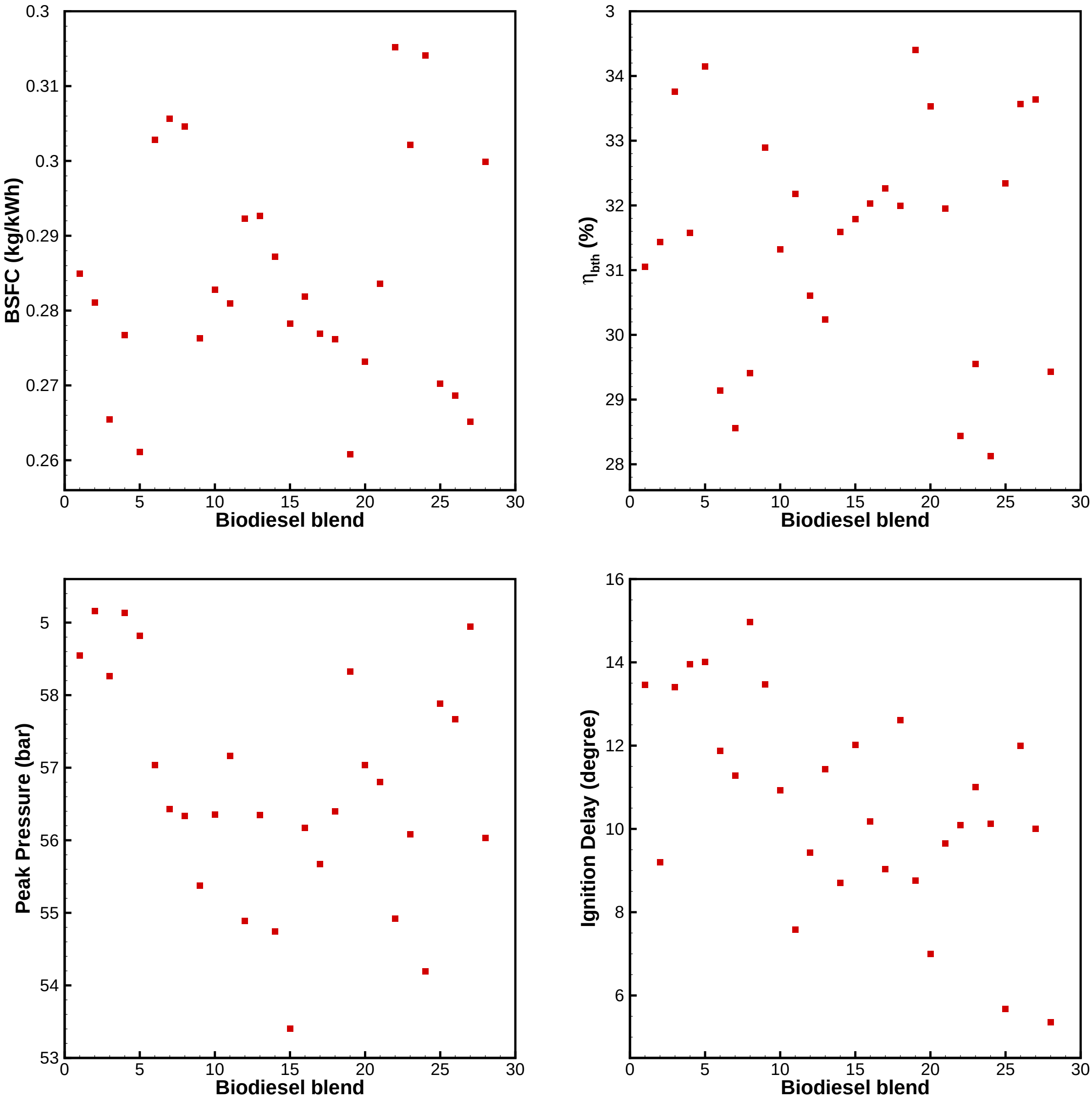

Figure 4.1: Performance and combustion analysis of the first phase- 28 experiments at 12 kg (100%) engine load (a) Brake specific fuel consumption vs biodiesel blend, (b) Brake thermal efficiency vs biodiesel blend, (c) Peak (maximum) pressure vs biodiesel blend, (d) Ignition delay vs biodiesel blend.

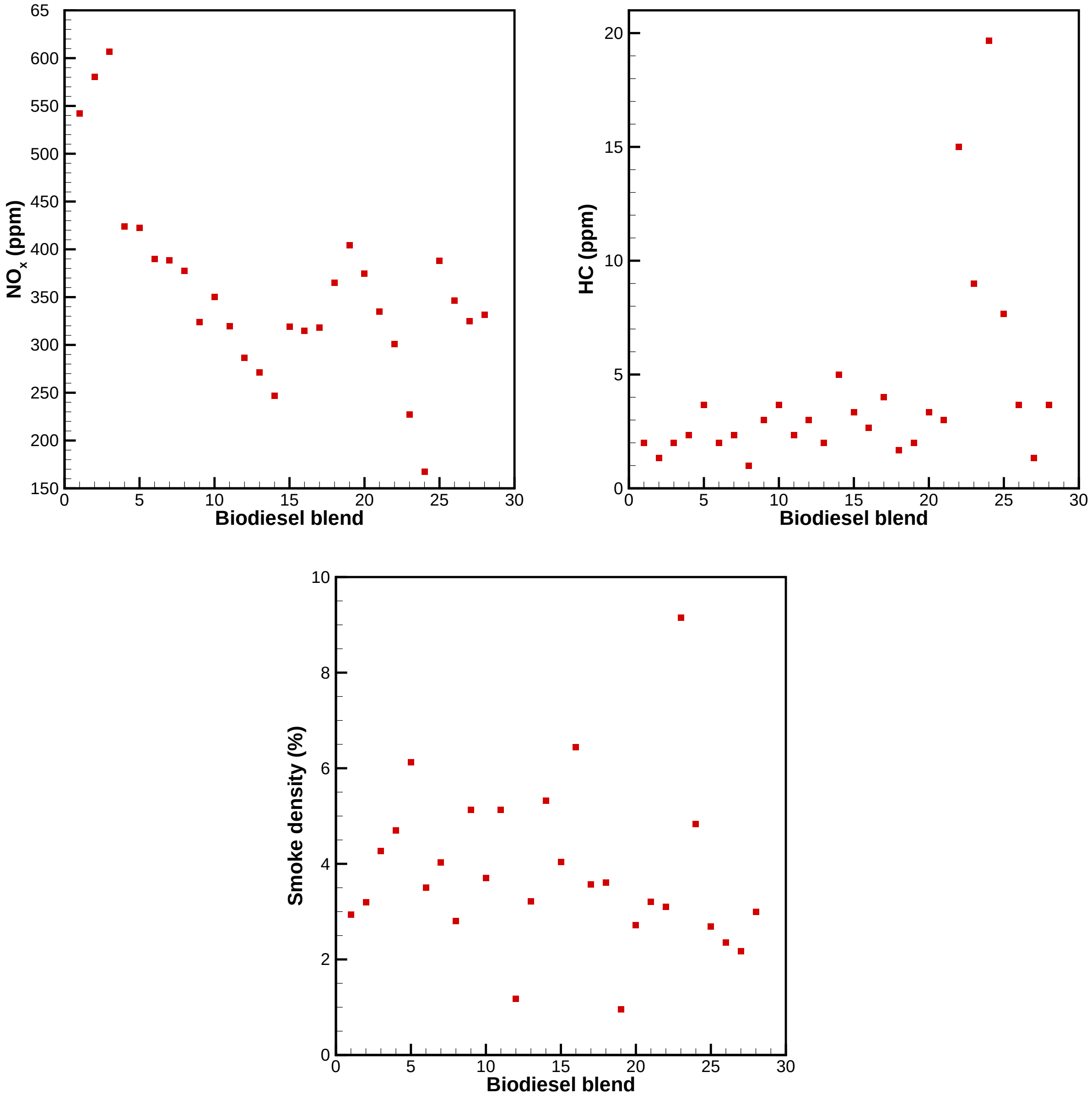

Figure 4.2: Emission analysis of the first phase- 28 experiments at 12 kg (100%) engine load (a) Amount of NO_x in the exhaust vs biodiesel blend, (b) Amount of HC in the exhaust vs biodiesel blend, (c) Amount of smoke density in the exhaust vs biodiesel blend.

4.3.1 Results of Topsis Method

The full form of TOPSIS is **T**echnique for **O**rder **P**reference by **S**imilarity to **I**deal **S**olution. The base concept of this method is that the optimum alternative should have the minimum distance from the ideal solution and the maximum distance from negative ideal solution. The decision matrix formed through the available information of attributes in Topsis method, consists of $'m'$ number of alternatives and $'n'$ number of attributes (criteria). Each column represents the values of specific attribute for different alternatives, while the each row represents the values of different attributes for specific alternative. So, x_{mn} represents the value of m^{th}alternative and n^{th}attribute.

$$\mathrm{D} = \begin{array}{c} \mathrm{A}_1 \\ \mathrm{A}_2 \\ \mathrm{A}_3 \\ . \\ . \\ . \\ \mathrm{A}_m \end{array} \left[\begin{array}{ccccccc} x_{11} & x_{12} & x_{13} & . & . & . & x_{1n} \\ x_{21} & x_{22} & x_{23} & . & . & . & x_{2n} \\ x_{31} & x_{32} & x_{33} & . & . & . & x_{3n} \\ . & . & . & & & & . \\ . & . & . & & & & . \\ . & . & . & & & & . \\ x_{m1} & x_{m2} & x_{m3} & . & . & . & x_{mn} \end{array} \right]$$

Where, A_1,A_2,...,A_m= m number of alternatives, x_{11},x_{12},...,x_{1n}= values of n no. of attributes for alternative 1.

Topsis method works on the three basic hypothesis:

1. There is a monotonically increasing or monotonically decreasing utility for each attribute in the decision matrix.
2. As per the hypothesis that no thing can be best in every aspects, a set of weights are always required for the given attributes.
3. Any outcome which is expressed through a non-numerical way, should be quantified by an appropriate scaling technique.

In our problem of finding best two biodiesels using Topsis method, we are using the table 4.3 as a decision matrix for calculating the ranks of 28 different biodiesel blends. Here, 28 different biodiesel blends are our alternatives, while the seven attributes are BSFC, BTHE, Peak pressure, Ignition delay, $\mathrm{NO_x}$, HC and smoke emission. The level of satisfaction (objective) for BTHE and Peak pressure is higher the better, whereas the level of satisfaction for BSFC, Ignition delay, $\mathrm{NO_x}$, HC and smoke emission is lower the better. The first requirement of Topsis method is to form the normalized input values. As the measuring units of given seven attributes are different, first we have to convert the given result values in non-dimensional values by dividing each value with the square root of the summation of the square values of respective attribute column. The resulted matrix is called as normalized decision matrix, r_{ij}.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum\limits_{i=1}^{m} x_{ij}^2}}$$

Now the relative weightage is assigned to the given seven attributes as discussed in4.3. The sum of weights, ($\sum w_j = w_1 + w_2 + ... + w_n$) is always one. This relative weightage is multiplied with the corresponding attribute column values for getting the weighted normalized decision matrix V_{ij}.

$$V_{ij} = w_j \times r_{ij}$$

Topsis method is deciding the rank of the given alternatives on the basis of the ideal solution A^+ and negative ideal solution A^- of attribute column values of weighted normalized matrix V_{ij}. At ideal condition, all the attributes are attaining their highest level of satisfaction value, while at negative-ideal condition, all the attributes are attaining their lowest level of satisfaction value.

Ideal Solution, A^+

$$A^+ = \left\{ \left(\begin{matrix} max & v_{ij} | j \in J \\ i & \end{matrix} \right), \left(\begin{matrix} min & v_{ij} | j \in J' \\ i & \end{matrix} \right) | i = 1, 2, .., m \right\}$$

$$A^+ = \left\{ v_1^+, v_2^+, v_3^+, ..., v_j^+, ..., v_n^+ \right\}$$

Negative ideal solution,A^-

$$A^- = \left\{ \left(\begin{matrix} min & v_{ij} | j \in J \\ i & \end{matrix} \right), \left(\begin{matrix} max & v_{ij} | j \in J' \\ i & \end{matrix} \right) | i = 1, 2, .., m \right\}$$

$$A^- = \left\{ v_1^-, v_2^-, v_3^-, ..., v_j^-, ..., v_n^- \right\}$$

Where,

$J = \{1, 2, .., n | j$ associated with benefit criteria$\}$

$J' = \{1, 2, .., n | j$ associated with cost criteria$\}$

So, in the ideal solution A^+, we are selecting the values of lowest BSFC, highest BTHE, highest peak pressure, lowest Ignition delay, lowest engine exhausts NO_x, HC and smoke density from the respective attribute columns of weighted normalized matrix V_{ij}. Similarly, for the negative ideal solution A^-, we are selecting the values of highest BSFC, lowest BTHE, lowest peak pressure, highest Ignition delay, highest engine exhausts NO_x, HC and smoke density from the respective attribute columns of weighted normalized matrix V_{ij}. Now, the ideal separation $S_i^+$and negative-ideal separation S_i^- of each attribute value of respected alternative (biodiesel blend) from the ideal and negative-ideal solution of that attribute column is calculated as per following formula:

Ideal separation:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+ \right)^2}, \ i = 1, 2, ..., m$$

Negative-ideal separation:

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}, \; i = 1, 2, ..., m$$

For ideal separation, the corresponding ideal solution is subtracted from the respective attribute column values of weighted normalized matrix and the square of the resulted value is done. For the negative ideal separation, the corresponding negative ideal solution is subtracted from the respective attribute column values of weighted normalized matrix and the square of the resulted value is done. The row-wise summation of seven attribute values for each alternative (biodiesel blend) of ideal separation matrix and negative-ideal separation matrix is done for finding the ideal separation S_i^+ and negative-ideal separation S_i^- respectively. Then the relative closeness coefficient C_i^* is calculated according to following formula for finding the closeness of each alternative (biodiesel blend) to the ideal solution of 1.

$$C_i^* = \frac{S_i^-}{S_i^+ + S_i^-}$$

Where, $0 < C_i^* < 1$ and $i = 1, 2, 3, ..., m$

If for given alternative $C_i^* = 1$, then that alternative is Ideal solution A^+. If for given alternative $C_i^* = 0$, then that alternative is Negative-ideal solution A^-. The ranking to the biodiesel blends is assigned on the basis of descending value of C_i^*. The biodiesel blend having the highest value of $C_i^*$is the best optimum solution, while the biodiesel blend having the lowest value of $C_i^*$is the worst solution.

4.3.2 Results of Promethee Method

The full form of Promethee is **P**reference **R**anking **O**rganization **METH**od of **E**nrichment **E**valuation. It has an outranking nature and is based on the approach of preference function. The preference function $P_j\left(a, b\right)$ of alternatives a and b is defined as the preference difference d_j between the values of $f_j\left(a\right)$and $f_j\left(b\right)$for the criterion j and the criterion function. The parameter q_j signifies the indifference threshold value that represents the largest difference between attribute values, which is considered as a decision number by the decision maker for calculating the preference function value as 0 or 1 during the comparison of two alternatives on that criterion. The parameter p_j represents the smallest difference that defines a range into which the value of preference function for one of the two alternatives will lie in between 0 and 1. There are the six types of criterion functions for Promethee method as shown in table 4.4.

Table 4.4: Types of criterion function and corresponding preference function values

Sr. No.	Criterion Functions	Preference function values for various criterion functions
1	Usual criterion	$H\left(d_j\right) = \begin{bmatrix} 0 \ \mathit{if} \ d_j = 0 \\ 1 \ \mathit{if} \ d_j > 0 \end{bmatrix}$
2	Quasi criterion	$H\left(d_j\right) = \begin{bmatrix} 0 \ \mathit{if} \ d_j \leq q_j \\ 1 \ \mathit{if} \ d_j > q_j \end{bmatrix}$
3	Criterion with linear preference and no indifference area	$H\left(d_j\right) = \begin{bmatrix} \frac{d_j}{p_j} \ \mathit{if} \ d_j \leq p_j \\ 1 \ \mathit{if} \ d_j > p_j \end{bmatrix}$
4	Level criterion	$H\left(d_j\right) = \begin{bmatrix} 0 \ \mathit{if} \ d_j \leq q_j \\ 0.5 \ \mathit{if} \ q_j < d_j \leq p_j \\ 1 \ \mathit{if} \ d_j > p_j \end{bmatrix}$
5	Criterion with linear preference and indifference area	$H\left(d_j\right) = \begin{bmatrix} 0 \ \mathit{if} \ d_j \leq q_j \\ \frac{(d_j - q_j)}{(p_j - q_j)} \ \mathit{if} \ q_j < d_j \leq p_j \\ 1 \ \mathit{if} \ d_j > p_j \end{bmatrix}$
6	Gaussian criterion	$H\left(d_j\right) = \left[1 - e^{\frac{-d_j^2}{2\sigma_j^2}}\right]$ $\sigma_j^{'}$ is the distance between the origin and the point of inflexion of the considered preference function.

The type of decision matrix formed in this method is as follows:

$$
D = \begin{array}{c} A_1 \\ A_2 \\ A_3 \\ . \\ . \\ . \\ A_m \end{array}
\begin{bmatrix}
x_{11} & x_{12} & x_{13} & . & . & . & x_{1n} \\
x_{21} & x_{22} & x_{23} & . & . & . & x_{2n} \\
x_{31} & x_{32} & x_{33} & . & . & . & x_{3n} \\
. & . & . & & & & . \\
. & . & . & & & & . \\
. & . & . & & & & . \\
x_{m1} & x_{m2} & x_{m3} & . & . & . & x_{mn}
\end{bmatrix}
$$

Where, A_1,A_2,...,A_m= m number of alternatives, x_{11},x_{12},...,x_{1n}= values of n no. of attributes for alternative 1.

Here also, we are using the table 4.3 as a decision matrix for calculating the ranks of 28 different biodiesel blends. The 28 different biodiesel blends are our alternatives, while the seven attributes are BSFC, BTHE, Peak pressure, Ignition delay, NO_x, HC and smoke density. The level of satisfaction (objective) for BTHE and Peak pressure is higher the better, while the level of satisfaction for BSFC, Ignition delay, NO_x, HC and smoke emission is lower the better. Due to different measuring units of given seven attributes, first we have to convert the given values of decision matrix non-dimensional values. Negative sign is assigned to the BSFC, Ignition delay, NO_x, HC and smoke density values for analyzing the entire problem uniformly in the perspective of maximization. For the sake of simplicity, Transpose of the decision matrix is taken, in which all the attribute column values are converted into row values. The resulted matrix formed will be as follows:

$$\mathrm{D}^{\mathrm{T}} = \begin{array}{c} \mathrm{C}_1 \\ \mathrm{C}_2 \\ \mathrm{C}_3 \\ . \\ . \\ . \\ \mathrm{C}_n \end{array} \begin{bmatrix} -x_{11} & -x_{21} & -x_{31} & . & . & . & -x_{m1} \\ -x_{12} & -x_{22} & -x_{32} & . & . & . & -x_{m2} \\ -x_{13} & -x_{23} & -x_{33} & . & . & . & -x_{m3} \\ . & . & . & & & & . \\ . & . & . & & & & . \\ . & . & . & & & & . \\ -x_{1n} & -x_{2n} & -x_{3n} & . & . & . & -x_{mn} \end{bmatrix}$$

Where, C_1,C_2,...,C_n= n number of attributes.

Now the pairwise difference between the attribute values of each alternative (biodiesel blend) is taken. Here, for the specific attribute, the attribute values of all alternatives (biodiesel blends) are subtracted from the attribute value of first alternative (biodiesel blend) for getting the first row of pairwise difference matrix of that attribute. The attribute values of all alternatives are subtracted from the attribute value of second alternative for getting the second row of pairwise difference matrix of that attribute. Similar procedure is followed for successive rows of pairwise difference matrix. For seven attributes, we are getting the total seven pairwise difference matrices and each pairwise difference matrix is 28 × 28. There are many types of preference functions, but for our problem, we are selecting the usual criterion preference function. In the usual criterion, the preference function value of 0 is assigned for negative pairwise difference and the preference function value of 1 is assigned for positive pairwise difference. For seven pairwise difference matrices, we are getting the seven preference function matrices of 28 × 28. The multi-criterion preference index, $\pi\left(\mathrm{A}_m, \mathrm{C}_n\right)$ is defined as follow:

$$\pi\left(\mathrm{A}_m, \mathrm{C}_n\right) = \frac{\sum_{j=1}^{n} w_j P_j\left(m, n\right)}{\sum_{j=1}^{n} w_j}$$

The multiplication of corresponding preference function values of seven preference function matrices is done with the weights associated with corresponding attributes. The summation of these values of seven attributes of specific alternative (biodiesel blend) is done and dividing it with the summation of the all weights $\sum w_j = 1$. This way, we are getting the weighted average value or multi-criterion preference index value of the seven preference function matrices for the specific alternative. Similar procedure is followed for getting the weighted average values of rest of the alternatives. For getting ranks of the alternatives, we are calculating the outranking index $\phi^+ (m)$ and outranked index$\phi^- (m)$ as per following formula:

$$\phi^+ (m) = \frac{\underset{A}{\sum} \pi \left(\mathrm{A}_m, \mathrm{C}_n\right)}{m-1}$$

$$\phi^- (m) = \frac{\underset{A}{\sum} \pi \left(\mathrm{C}_n, \mathrm{A}_m\right)}{m-1}$$

For $\phi^+ (m)$, the summation of the row values of multi-criterion preference index matrix is done and dividing it with the value of (number of alternatives - 1). For $\phi^- (m)$, the summation of the column values of multi-criterion preference index matrix is done and dividing it with the value of (number of alternatives - 1). Net $\phi (m)$ index is calculated as:

$$\phi (m) = \phi^+ (m) - \phi^- (m)$$

The ranking to the biodiesel blends (alternatives) is assigned on the basis of decreasing value of $\phi (m)$. The biodiesel blend having the highest value of $\phi (m)$ is the best optimum solution, while the biodiesel blend having the lowest value of $\phi (m)$ is the worst solution.

Figure 4.3 shows the ranks given to the different biodiesel blends according to the results of two optimization methods Topsis and Promethee.

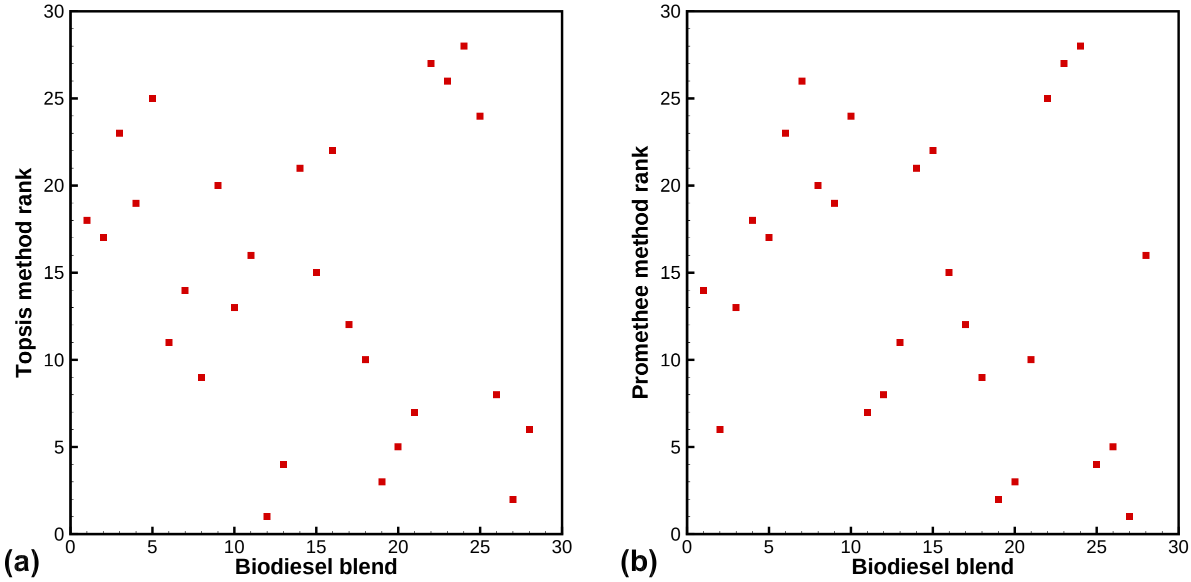

Figure 4.3: Ranks assigned to 28 different biodiesel blends as per the results of two optimization methods (a) Topsis method, (b) Promethee method.

4.3.3 Spearman's Rank Correlation

It can be happened that the selected two optimization methods Topsis and Promethee can give the results, those are different from each other. Moreover, each optimization method has its own set of steps and formulas for calculating the solution of given optimization problem and it assigns the ranks to the given variables (alternatives) in different way. So, for the given same optimization problem, two different optimization methods can give the different ranks to the given variables. In such cases, we have to find the way of relating the results of two methods and from that we can find which optimization method is more suitable for the given problem. Such relation between the results of two optimization methods can be found out by the parameter called the spearman's rank correlation. Spearman's rank correlation coefficient $'\rho'$ is the non-parametric monotonic relation between the two sets of quantitative variables. The value of $'\rho'$ lies from -1 to $+1$. The closest value of $'\rho'$ towards the $+1$ shows the stronger monotonic relation between the ranks given by two optimization methods. Spearman's rank correlation $'\rho'$ can be found out using following formula:

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}$$

where, d_i is the pairwise difference between the ranks given by two optimization methods and n is the number of variables in associated with the problem. For our case, value of n is 28. Table 4.5 shows the ranks of 28 different biodiesel blends as per the Topsis and

Promethee method. We can see that as per the Topsis method, Karanja-Rapeseed is the best blend of diesel/biodiesels and Linseed-Rapeseed is the worst blend of diesel/biodiesels on the basis of engine performance, combustion and emission. In both the best blend and worst blend, there is the Rapeseed biodiesel as common, which raises the question on Rapeseed biodiesel. As per the Promethee method, Castor-Jatropha is the best blend of diesel/biodiesels and Linseed-Rapeseed is the worst blend of diesel/biodiesels on the basis of engine performance, combustion and emission. In both the best blend and worst blend, there is no common biodiesel. Some biodiesel blends have higher ranks in Topsis method and lower ranks in Promethee method. Karanja-Rapeseed has the first rank in Topsis method, whereas it has eighth rank in Promethee method. There are some major and minor differences in the ranks of 28 biodiesel blends given by these two methods. When we are taking the absolute differences of the ranks given by Topsis and Promethee methods, we are getting the real picture. The biodiesel blend having the lowest absolute difference and highest rank in both Topsis and Promethee method is the best biodiesel blend for engine performance, combustion and emission. In this way, we have the two options Neem-Linseed and Castor-Jatropha. Both the biodiesel blends have same absolute difference of ranks and it is 1. But the Neem-Linseed has third rank in Topsis method and second rank in Promethee method, whereas Castor-Jatropha has second rank in Topsis method and first rank in Promethee method. So, with reference to the ranking of these two blends in Topsis and Promethee method, the best biodiesel blend is Castor-Jatropha in terms of engine performance, combustion and emission. The square of absolute differences ranks of these two methods is also shown in table 4.5. The value of spearman's rank correlation coefficient $'\rho'$ for the ranks of these two methods is coming as 0.55, which shows that the results of these two methods are related to each other and our final result Castor-Jatropha is the best blend by comparing the results of these two methods.

Table 4.5: Ranks of 28 different biodiesels according to Topsis and Promethee method and their absolute deviation

Sr. no.	Topsis rank	Promethee rank	Absolute deviation	square	Sr. no.	Topsis rank	Promethee rank	Absolute deviation	square
1	18	14	4	16	15	15	22	7	49
2	17	6	11	121	16	22	15	7	49
3	23	13	10	100	17	12	12	0	0
4	19	18	1	1	18	10	9	1	1
5	25	17	8	64	19	3	2	1	1
6	11	23	12	144	20	5	3	2	4
7	14	26	12	144	21	7	10	3	9
8	9	20	11	121	22	27	25	2	4
9	20	19	1	1	23	26	27	1	1
10	13	24	11	121	24	28	28	0	0
11	16	7	9	81	25	24	4	20	400
12	1	8	7	49	26	8	5	3	9
13	4	11	7	49	27	2	1	1	1
14	21	21	0	0	28	6	16	10	100

4.4 Engine Performance, Combustion and Emission Analysis of Second Phase-6 Experiments

As mentioned in the subsection 4.3.3, Castor-Jatropha are selected as best two biodiesels on basis of two engine performance, two combustion and three emission parameters. Now, the second phase of experiments are conducted, in which we are finding the optimum percentage of these two best biodiesels. The percentage of two biodiesels in a blend are reduced from 50% to 30%, while the percentage of diesel is increased from 50% to 70%. Five experiments are performed for five different blends of Castor-Jatropha as 25% Castor 5% Jatropha, 20% Castor 10% Jatropha, 15% Castor 15% Jatropha, 10% Castor 20% Jatropha and 5% Castor 25% Jatropha, in which the percentage of diesel is remained as 70% constant. A experiment with 100% diesel is also carried out for comparing the results of these five experiments. The test procedure and the test operating conditions as compression ratio, injection timing and injection pressure are kept as same as kept during the first phase- 28 experiments. Table 4.6 shows the numbers used for the notations of the Castor-Jatropha/diesel blends in the various plots of second phase-6 experiments. Table 4.7 shows the calorific values of the Castor-Jatropha/diesel blends used in these 6 experiments.

Table 4.6: Notations used for Castor-Jatropha/diesel blends for the plots of second phase-6 experiments

Notation no.	Castor-Jatropha/diesel blend
1	Castor 25 Jatropha 5
2	Castor 20 Jatropha 10
3	Castor 15 Jatropha 15
4	Castor 10 Jatropha 20
5	Castor 5 Jatropha 25
6	Diesel 100

Table 4.7: Calorific values of Castor-Jatropha/diesel blends for second phase-6 experiments

Sr. No.	Castor-Jatropha/diesel blend	Calorific Value (kJ/kg)
1	Castor 25 Jatropha 5	41072.75
2	Castor 20 Jatropha 10	41245.5
3	Castor 15 Jatropha 15	41418.25
4	Castor 10 Jatropha 20	41591
5	Castor 5 Jatropha 25	41763.75
6	Diesel 100	43000

4.4.1 Engine Performance Analysis of Second Phase Experiments

Figure 4.4 shows the plots of performance parameters as mass of fuel consumed ($\dot{m}_f$), Brake thermal efficiency (BTHE), Brake specific fuel consumption (BSFC), Brake specific energy consumption (BSEC) and Brake power (BP) for the five different Castor-Jatropha blend tests and one 100% diesel test. Castor-Jatropha blends have 2.5-5% lower calorific value than pure diesel. It is concluded from literature that biodiesel blends have higher BSFC, slightly higher BTHE and lower brake power due to its lower calorific value and also for the same volume of fuel consumed, more mass of biodiesel is to be supplied compared to diesel for producing the same power. Figure 4.4a shows that the mass of fuel consumed ($\dot{m}_f$) increases with the increase in engine load due to requirement of more fuel to sustain the higher load operation. The pure (100%) diesel has lowest mass of fuel consumed at all loads due to its higher calorific value and lower density. Castor 25 Jatropha 5 has slightly higher mass of fuel consumed compared to pure diesel for all loads. All other Castor Jatropha blends have higher ($\dot{m}_f$) value compared to pure diesel and Castor 25 Jatropha 5. At lower and medium loads (0, 3, 6 and 9), Castor 10 Jatropha 20 has higher ($\dot{m}_f$) value, while at higher loads (12 and 13.2 kg), Castor 15 Jatropha 15 has higher value of ($\dot{m}_f$). According to figure 4.4b, Castor 25 Jatropha 5 has higher brake thermal efficiency (BTHE) at 9 kg and 12 kg engine loads. At 0 kg, Castor 5 Jatropha 25 has higher BTHE, while it has second higher BTHE after pure diesel at 3 kg. Castor 15 Jatropha 15 and Pure diesel has higher BTHE at 6 kg and 13.2 kg loads respectively. The BTHE of different Castor-Jatropha/diesel blends is increasing with the increase in the engine load due to more efficient combustion of fuel at higher cylinder pressure and temperature. 8-10% higher oxygen content and the lower calorific value of different Castor-Jatropha blends provides the higher BTHE. The Castor 25 Jatropha 5 blend has 0.7 to 5% higher BTHE than pure diesel at higher loads (12 and 13.2 kg). As per the figure 4.4c,with increase in the engine load, the value of BSFC decreases for all fuels due to the requirement of less fuel at higher loads for producing the same amount of power because of higher cylinder pressure and temperature. Pure diesel has highest brake specific fuel consumption (BSFC) at no load (0 kg) due to the generation of very large friction power. At 3 kg and 13.2 kg load, pure diesel has lower value of BSFC. Castor 15 Jatropha 15 has lower BSFC at 6 kg. Castor 25 Jatropha 5 has lower BSFC at 9 kg and 12 kg. Overall, the Castor-Jatropha blends have lower BSFC compared to pure diesel for higher loading operations. Figure 4.4d shows the plots of brake specific energy consumption (BSEC) for various engine loading. BSEC is the product of BSFC and fuel calorific value that defines how much MJ of fuel energy is consumed for generating 1 kWh of brake power. BSEC shows that how effectively the energy contained in the fuel is used for generating the brake power. Lower BSEC is always desirable. With increase in engine loading, the value of BSEC is decreasing. Pure diesel has higher BSEC at no load due to more frictional power. Castor 25 Jatropha 5 has lower BSEC at 9 kg and 12 kg load. Pure diesel has lower value of BSEC at 3 kg and 13.2 kg load. At 6 kg load, Castor 15 Jatropha 15 has lower BSEC. Figure 4.4e shows the plots of brake power (BP) vs engine loading. At no load (0 kg), Pure diesel has lower BP due to large friction power, while the Castor 5 Jatropha 25 has higher BP at no load. Pure diesel has higher brake power at 3 kg and 13.2 kg. Castor 15 Jatropha 15, Castor 25 Jatropha 5 and Castor 5 Jatropha 25 have higher brake power at 6 kg, 9 kg and 12 kg respectively.

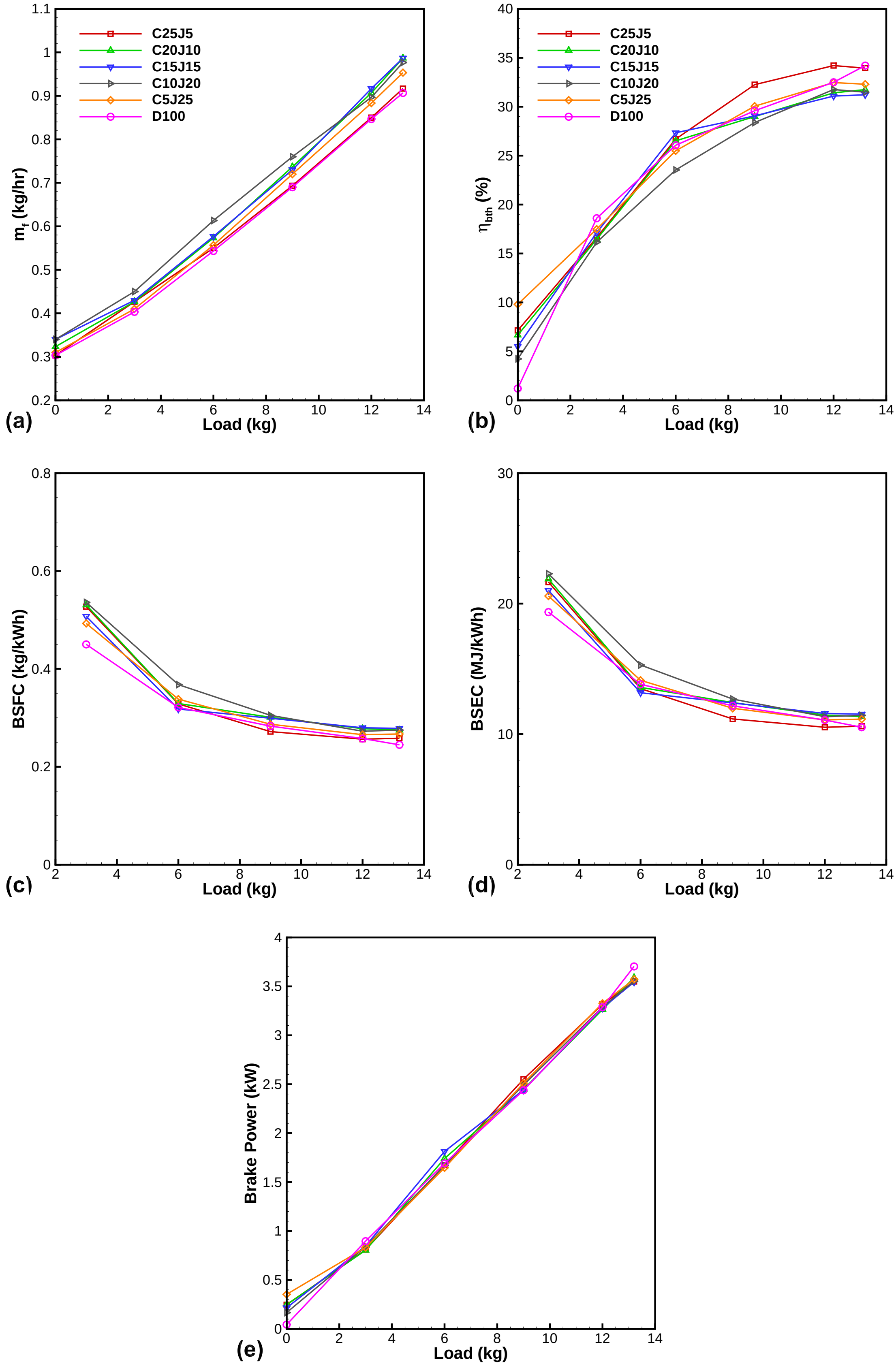

Figure 4.4: Performance analysis of the second phase-6 experiments using Castor-Jatropha blends (a) Mass of fuel consumed vs engine load, (b) Brake thermal efficiency vs engine load, (c) Brake specific fuel consumption vs engine load, (d) Brake specific energy consumption vs engine load, (e) Brake power vs engine load.

4.4.2 Engine Combustion Analysis of Second Phase Experiments

Figure 4.5 shows the plots of pressure-crank angle, net heat release, peak pressure, maximum $(dp/d\theta)_{max}$ and ignition delay period. Here, we have done the combustion analysis at full load (12 kg) engine operation. Figure 4.5a shows the plots of cylinder pressure during the combustion vs the crank angle for five different Castor-Jatropha blends and pure diesel. From this graph, the peak pressure is obtained. Figure 4.5c shows the plots of peak pressure and crank angle of peak pressure occurring for castor-Jatropha blends and pure diesel. Highest peak pressure is occurred for Castor 25 Jatropha 5 blend, while the lowest peak pressure is occurred for pure diesel. With decrease in the percentage of Castor biodiesel or with increase in the percentage of Jatropha biodiesel in the blend, the value of peak pressure decreases. The peak pressure of Castor 25 Jatropha 5, Castor 20 Jatropha 10, Castor 15 Jatropha 15 blends and pure diesel are occurred at 18^o ATDC (378^o), whereas the peak pressure of Castor 10 Jatropha 20 and Castor 5 Jatropha 25 blends are occurred at 19^o ATDC (379^o). Figure 4.5b shows the plots of net heat release during the combustion of five different Castor-Jatropha blends and pure diesel. From these plots the ignition delay period of these five blends and pure diesel is calculated. The injection angle of 20^o BTDC is kept constant for all experiments. Ignition delay period is the time interval in terms of crank angle between the start of fuel injection and start of combustion. As shown in figure 4.5b, the net heat release of fuel combustion is negative during the initial stages of fuel injection. During initial stages, the injected atomized fuel absorbs the heat from the already compressed high temperature air and starts vaporizing. The reaction between the fuel molecules starts in the absence of flame that known as pre-flame combustion. The rate of net heat absorption is higher than the rate of net heat release during pre-flame combustion. Due to this, the cylinder pressure decreases and attends the minimum value, where the rate of net heat absorption is equal to the rate of net heat release. Now on-wards, cylinder pressure increases due to increase in the rate of net heat release as the combustion of fuel starts. This rise of rate of net heat release fills the loss of heat energy occurred during pre-flame combustion and attends the initial zero condition of net heat release. From this, the net heat release is continuously increases and attend the maximum value. The difference of the crank angle between the start of fuel injection and the start of the rise of the net heat release from the '0' value gives the ignition delay period. Figure 4.5e shows the ignition delay period of five different Castor-Jatropha blends and pure diesel. Highest ignition delay is occurred for Castor 25 Jatropha 5 blend, whereas the lowest ignition delay is occurred for Castor 10 Jatropha 20 blend. Castor 10 Jatropha 20 and Castor 5 Jatropha 25 blends have lower ignition delay than pure diesel. Lower ignition delay reduces the accumulation of fuel during the pre-flame combustion and also reduces the chances of knocking during the uncontrolled combustion stage of the combustion cycle. Figure 4.5d shows the maximum rate of pressure rise, $(dp/d\theta)_{max}$ and occurrence of maximum $(dp/d\theta)_{max}$. Castor 25 Jatropha 5 blend has maximum rate of pressure rise, whereas Castor 15 Jatropha 15 blend has minimum rate of pressure rise. Castor 15 Jatropha 15 and Castor 10 Jatropha 20 blend have lower $(dp/d\theta)_{max}$ than pure diesel. Smoother combustion occurs for lower rate of pressure rise. The crank angle of $(dp/d\theta)_{max}$ is also shown in figure 4.5d.

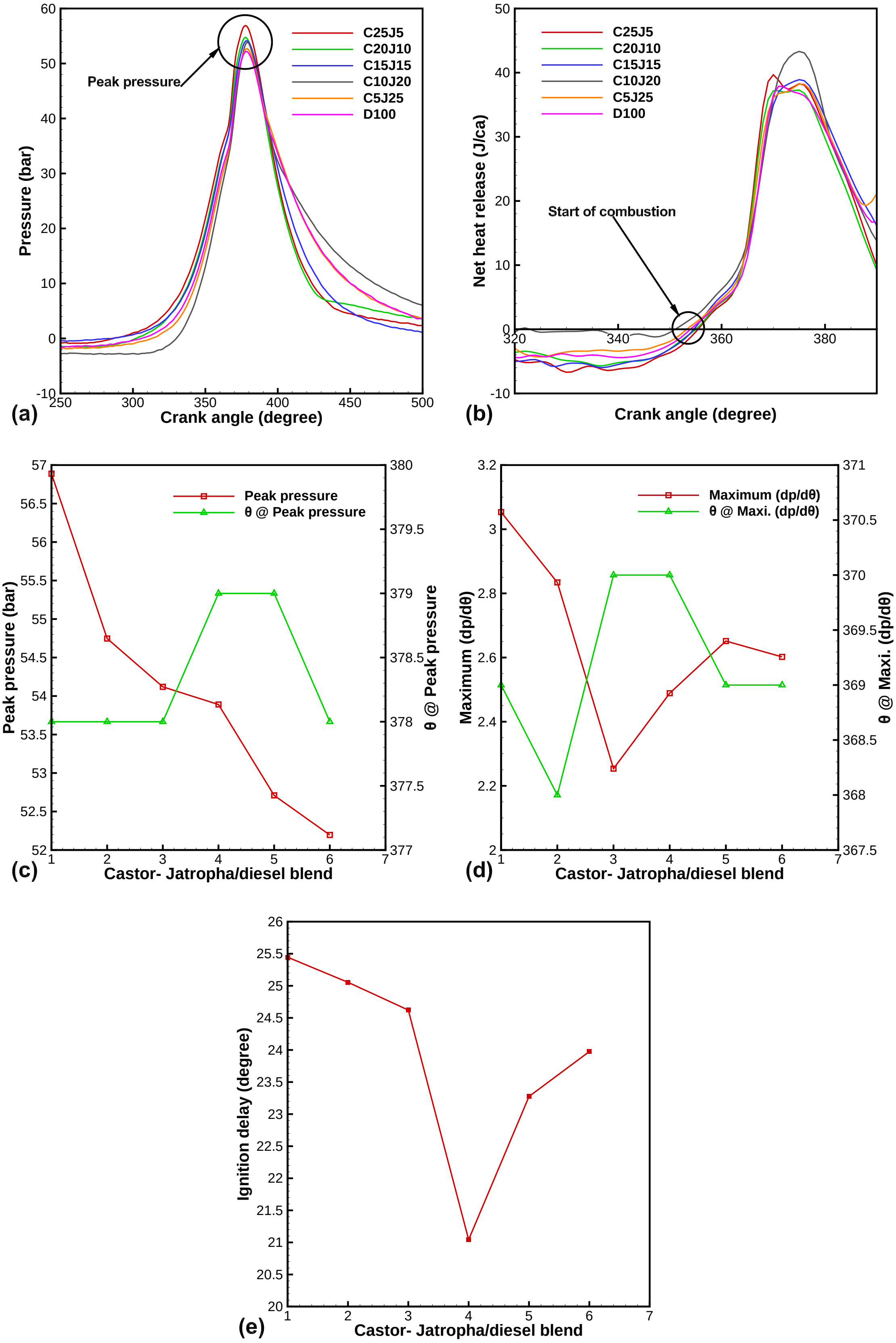

Figure 4.5: Combustion analysis of the second phase-6 experiments at 12 kg (100%) engine load using Castor-Jatropha blends (a) Pressure vs crank angle, (b) Net heat release vs crank angle, (c) Peak pressure and θ@ peak pressure vs Castor-Jatropha/diesel blend, (d) $(dp/d\theta)_{max}$ and θ@ $(dp/d\theta)_{max}$ vs Castor-Jatropha/diesel blend, (e) Ignition delay period vs Castor-Jatropha/diesel blend.

4.4.3 Engine Emission Analysis of Second Phase Experiments

Figure 4.6 shows the plots of engine exhaust gases CO, CO_2, HC, NO_x and smoke density of five different Castor-Jatropha blends and one pure diesel for various engine loading conditions. Literature says that the biodiesel blends reduces the CO, HC and smoke emissions, while it increases the NO_x emissions. Figure 4.6a shows the plots of CO emissions. CO emissions are produce by the incomplete combustion of fuel that occurs due to higher viscosity of fuel, lower cetane number, improper air-fuel ratio, poor atomization, less air turbulence and less fuel injection pressure. As per the plot 4.6a, with increase in engine load, the amount of CO emissions are decreasing due to occurrence of higher temperature and pressure in the combustion chamber at higher loading. Pure diesel has the highest CO emissions at no load. At lower loading of 0 kg and 3 kg, Castor 5 Jatropha 25 has lower CO emission. Castor 20 Jatropha 10 has lower CO emission at 6 kg load. Pure diesel has lower CO emission at 9 kg, 12 kg and 13.2 kg engine load. Castor 5 Jatropha 25 has second lower CO emission after pure diesel at 12 kg and 13.2 kg load. Figure 4.6b shows the plots of CO_2 emissions. Complete combustion of fuel produces the CO_2 emissions. Pure diesel has highest CO_2 emission at no load. At 3 kg, 6 kg and 9 kg, Pure diesel, Castor 15 Jatropha 15 and Castor 5 Jatropha 25 have lower CO_2 emission respectively. At the higher loading of 12 kg and 13.2 kg, pure diesel has lower CO_2 emission. Figure 4.6c shows the plots of HC emissions. During the combustion of fuel in CI engine, some fuel molecules are decomposed and remained as unburned due to lower rate of reaction. These decomposed and unburned fuel molecules contain sufficient number of carbon particles and hydrocarbons. These unburned hydrocarbons burn after the actual combustion of fuel during expansion stroke. Most of the time, they remained as unburned due to lack of oxygen and known as unburned hydrocarbons (HC). As shown in figure 4.6c, Castor 20 Jatropha 10 and Pure diesel have lower HC emission at 0 kg and 3 kg engine load respectively. At 9 kg and 12 kg, Castor 25 Jatropha 5 has lower HC emission. Castor 10 Jatropha 20 has lower HC emission at 13.2 kg. Figure 4.6d shows the plots of NO_x emission. Due to 8-10% more amount of oxygen content of biodiesel, the flame temperature of fuel combustion is higher as compared to diesel during high engine loading operation. This higher oxygen content and flame temperature enhances the reaction of environmental nitrogen with oxygen and produces the NO_x emissions. As per the figure 4.6d, the NO_x emissions are increasing with increase in engine load due to higher combustion temperature and pressure at higher loads. Castor 10 Jatropha 20 has lower NO_x emission at 0 kg, 3 kg and 6 kg engine load. Pure diesel has lower NO_x emission at 9 kg and 13.2 kg load. Castor 15 Jatropha 15 has lower NO_x emission at 12 kg load. Figure 4.6e shows the plots of smoke density. Castor 5 Jatropha 25 has lower smoke density at lower loads (0 kg, 3 kg), medium loads (6 kg, 9 kg) and at 13.2 kg. Castor 25 Jatropha 5 and Castor 10 Jatropha 20 have lower smoke density at 12 kg engine load.

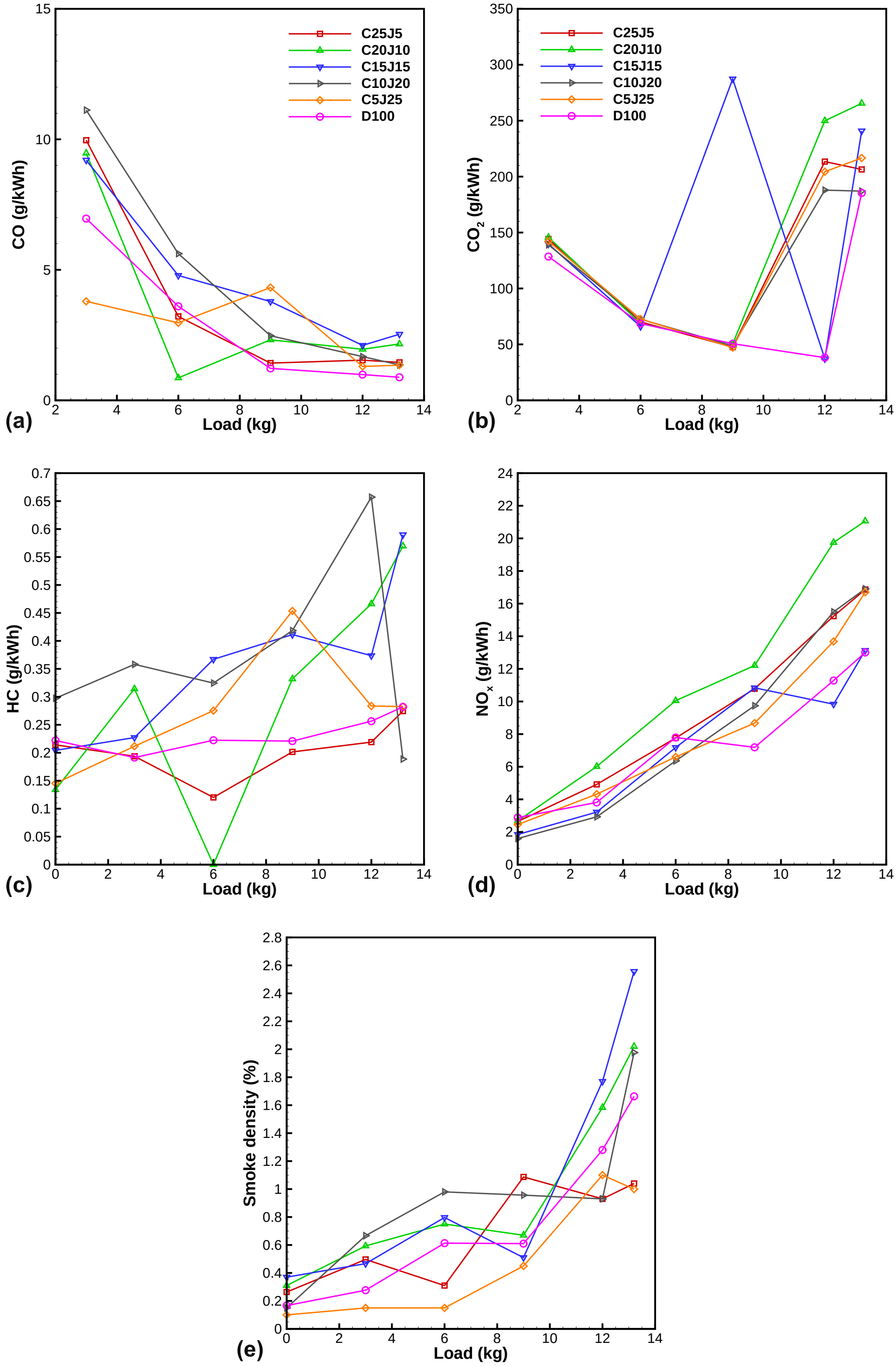

Figure 4.6: Emission analysis of the second phase-6 experiments using Castor-Jatropha blends (a) Amount of CO in the exhaust vs engine load, (b) Amount of CO_2 in the exhaust vs engine load, (c) Amount of HC in the exhaust vs engine load, (d) Amount of NO_x in the exhaust vs engine load, (e) Amount of smoke density in the exhaust vs engine load.

4.5 Topsis and Promethee Method Analysis for Second Phase- 6 Experiments

Our main aim is to find the optimum percentage of best two biodiesels. Castor-Jatropha is found as best two biodiesels by the results of Topsis and Promethee method for the first phase- 28 experiments. For finding the optimum percentage, we are conducted the 5 experiments using five different Castor-Jatropha blends. The test with 100% diesel is also conducted for the comparison with the results of these five experiments. Here also, we are using the Topsis and Promethee method for finding the ranks of these five different Castor-Jatropha blends and one pure diesel. Table 4.8 shows the results of second phase- 6 experiments at full load (12 kg) engine operation. This table 4.8 is used as a decision matrix in both Topsis and Promethee method. In both methods, the alternatives are taken as five different Castor-Jatropha blends and Pure diesel. The attributes used are BSFC, BTHE, Peak pressure, Ignition delay, NO_x, HC and Smoke density, which are same as used in previous Topsis and Promethee methods for first phase- 28 experiments. The level of satisfaction or objectives of the attributes, the relative weightage to the attributes and the procedures for calculating the ranks of Castor-Jatropha blends and pure diesel using the Topsis and Promethee methods are as same as used in previous Topsis and Promethee methods for first phase- 28 experiments.

Table 4.8: Performance, combustion and emission results of second phase- 6 experiments at full load engine operation for Topsis and Promethee method

Weightage	0.125	0.125	0.125	0.125	0.16667	0.16667	0.16667
Higher/Lower better	Lower	Higher	Higher	Lower	Lower	Lower	Lower
Attributes	BSFC	BTHE	Peak Pr.	I Delay	NO_x	HC	Smoke
Diesel/Biodiesel blend	kg/kWh	%	bar	degree	g/kWh	g/kWh	%
Castor 25 Jatropha 5	0.256	34.20	56.89	25.446	15.23	0.219	0.93
Castor 20 Jatropha 10	0.278	31.42	54.75	25.055	19.75	0.466	1.583
Castor 15 Jatropha 15	0.280	31.09	54.12	24.622	9.83	0.374	1.77
Castor 10 Jatropha 20	0.273	31.76	53.89	21.043	15.50	0.657	0.93
Castor 5 Jatropha 25	0.266	32.47	52.71	23.275	13.68	0.284	1.1
Diesel 100	0.258	32.50	52.20	23.975	11.28	0.256	1.28

Table 4.9 shows the ranks of these five different Castor-Jatropha blends and one pure diesel according to Topsis and Promethee methods using the results of second phase- 6 experiments. The absolute deviation between the ranks of two methods is also shown. The value of spearman's rank correlation coefficient $'\rho'$ for the table 4.9 is coming 0.89, which shows the quietly good relation between the ranks given by these two optimization methods. The blend having minimum deviation in ranking and having highest ranking in both Topsis and Promethee method is selected as optimum solution. We can see that the Castor 25 Jatropha 5 blend and pure diesel, both have minimum deviation of ranking as 1.

Castor 25 Jatropha 5 blend has second rank in Topsis method and first rank in Promethee method, while the pure (100%) diesel has first rank in Topsis method and second rank in Promethee method. So, based on the condition of having minimum deviation in ranking and having highest ranking in both Topsis and Promethee method, Castor 25 Jatropha 5 blend and Pure diesel are the optimum solutions. We want to find the optimum percentage of best two biodiesels, so our final optimum solution is a blend having 25% Castor, 5% Jatropha and 70% diesel.

Table 4.9: Ranks of five different Castor-Jatropha blends and one pure diesel according to Topsis and Promethee method along with their absolute deviation

Sr. no.	Castor-Jatropha/ Diesel blend	Topsis Rank	Promethee Rank	Absolute Deviation
1	Castor 25 Jatropha 5	2	1	1
2	Castor 20 Jatropha 10	6	6	0
3	Castor 15 Jatropha 15	4	5	1
4	Castor 10 Jatropha 20	5	4	1
5	Castor 5 Jatropha 25	3	3	0
6	Diesel 100	1	2	1

4.6 Closure

In this chapter, the results of first phase and second phase experiments and their discussion has been done. Topsis and Promethee methods are used to find the best two biodiesels and their optimum percentage in a single blend. 25% Castor, 5% Jatropha and 70% diesel is found to be the best biodiesel blend in terms of engine performance, combustion and emission parameters. The conclusion and the future work has been discussed in the next chapter.

Chapter 5

Conclusion and Future Work

The conclusion of the present work is listed below. The various analysis of present work is done with the 95% confidence level.

- Topsis and Promethee methods are applied to the results of first phase- 28 experiments. According to the ranks given by these two optimization methods, the Castro-Jatropha found as best two biodiesels in terms of engine performance, combustion and emission.
- The results of second phase- 6 experiments are also analyzed using Topsis and Promethee methods. According to the ranks given by these two optimization methods, the 25% Castor, 5% Jatropha and 70% diesel is found as optimum blend in terms of engine performance, combustion and emission. The spearman's rank correlation coefficient shows the very good relation between the ranks of Topsis and Promethee methods for second phase experiments.

We have performed the short term experiments on the engine using optimum biodiesel blend having 25% Castor, 5% Jatropha and 70% diesel. However, the long term experiments using the same optimum blend on the engine can be performed to know the engine performance, combustion and emission for long term running. The physical effect of this optimum blend on the various critical components of the CI engine for the long term engine operation can be studied. Wear and corrosion analysis of various CI engine components using this optimum blend is being currently carried out in our research group.

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