Study on use of Renewable Fuels in a Compression Ignition Engine

A Thesis submitted to the Delhi Technological University, Delhi in fulfillment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

in

Mechanical Engineering

by

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DECLARATION

I hereby declare that the thesis entitled "**Study on use of Renewable Fuels in a Compression Ignition Engine"** is an original work carried out by me under the supervision of Prof. Naveen Kumar, & Prof. Rajesh Kumar, Department of Mechanical Engineering, Delhi Technological University, Delhi. This thesis has been prepared in conformity with the rules and regulations of the Delhi Technological University, Delhi. The research work reported and results presented in the thesis has not been submitted either in part or full to any other university or institute for the award of any other degree or diploma.

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CERTIFICATE

This is to certify that the work embodied in the thesis "**Study on use of Renewable Fuels in a Compression Ignition Engine"** by **Sunil Kumar Sinha, (**Roll No.- **2K14/PhD/ME/12)** in partial fulfilment of requirements for the award of Degree of **DOCTOR OF PHILOSOPHY in Mechanical Engineering**, is an authentic record of student's own work carried by him under my supervision. This is also certified that this work has not been submitted to any other Institute or University for the award of any other diploma or degree.

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Dedicated to

My beloved late Maa

Shreemati Lalita Devi

&

Late Pitajee

Shree Mahabir Prasal Lal

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(Sunil Kumar Sinha)

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ABSTRACT

In the backdrop of rising transportation and Industrial air pollution, air quality is a major concern for human health and environmental degradation. The air quality level in India has also reached the critical stage, particularly in the winter season. To mitigate both concerns, the Government of India has adopted the BS-VI emission and fuel from 1st April 2020. In these standard norms, sulphur contains in petroleum diesel is going to reduce which affects the lubrication property of fuel. Furthermore, HC and NOx emission is also reduced. The implementation of BS-VI norms is a major challenge in the diesel engine manufacturing sector and huge investment is required to modification of engine to achieve the BS-VI.

After reviewing the number of significant research articles of this area it was found that the problem of lower sulphur content (low lubricity) in fuel and higher HC emissions can be addressed by the use of biodiesel instead of engine modification. However, the use of biodiesel or blend of biodiesel with diesel was improved the lubricity and HC emission but increased the NOx emission which negating the BS-VI emissions. Therefore, to reduce the NO_X emissions and kinematic viscosity and density of biodiesel, many researchers use the blend of alcohol with biodiesel, Moreover NOx reduction was achieved but the performance of the engine was compromised. From the last two decades, a lot of work was carried out on biodiesel particularly on jatropha biodiesel but the use of available jatropha biodiesel was underutilized, due to higher viscosity and higher NOx emission. Because biodiesel, still used as an extender fuel in the CI engine. However, the potential substitute for mineral diesel is still undetermined.

Hence, in this research, a small capacity diesel engine is used that is widely used in the agriculture sector. An effort is made to explore the effective utilize of jatropha

biodiesel with a blend of n-butanol and n-octanol which can completely replace the petroleum diesel without compromising the performance and emissions characteristics of an unmodified diesel engine. Jatropha is the most versatile inedible oil for easily manufacturing of biodiesel, which is supported by GOI biofuel policy. Recently trial of JME as an aviation fuel also boost its presence as an alternative fuel. Butanol is biomass-derived renewable alcohol such as ethanol while the n-octanol is synthesized by the petrochemical process of ethylene and n-heptane. It can also be produced from biomass.

The jatropha oil was extracted from the jatropha seeds. The four variable parameters were used for a reduction in FAA from 7.1% to 1.7 %, during the esterification process. The value of that parameter was the catalytic concentration of 1.13, reaction temperature 58°C reaction time 67 minutes, and molar ratio 6.35. The transesterification for biodiesel production was also optimized through design expert software and RSM was adopted for reduction of production cost and maximizes the production yield up to 96.63 %. The value of optimised parameters was molar ratio 7.52, the catalytic concentration of 0.83, reaction temperature 48°C reaction time 72 minutes. The JOME produced by using the optimized parameters and analytical grade n-butanol and n-octanol was purchased from standard chemical suppliers. The blend of n-butanol and n-octanol with JOME was prepared in 10% and 20% by volume. The characterization of fuel and blend was measured as per ASTM standard and compared with diesel. The viscosity of samples was slightly higher than diesel, however, it suitably conformed to ASTM D6751. The test rig was developed with Kirloskar make engine model TV-1 having rated power of 5.2 kW and experimental work emission, performance, and combustion analysis was carried out with a blend of JOME90B10, JOME80B20, JOME90O10, JOME80O20 and JOME100 and compare with base fuel D100.

The maximum brake thermal efficiency of 29.75 % was obtained by JOME80O20 at 80% load which is 18.34 % higher than BTE of JOME100. The HC and CO emissions of all tested fuels are much lower compared to conventional diesel fuel for all loading conditions. The addition of alcohol leads to HC emissions as compare to JOME100 but this change is marginal. The JOME80O20 emits 17.11% lower HC emission and 54.76% CO emission as compared to a conventional diesel engine. The NO_X emissions of JOME80O20 is 9.54% lower than JOME100 but comparable to a conventional diesel engine. A notable observation of blend of n-butanol and n-octanol with JOME was a notice in combustion analysis. The blend of JOME80O20 achieved the highest in-cylinder pressure 72.68 bar among all blend including diesel and JOME and also shown highest HRR 60.95 J/^{0}CA and RPRs 6.38 bar/^{0}CA but rather than diesel. Higher CHRR was observed for JOME80O20 while the lowest was for JOME100. The blend of n-octanol, shown more CHRR compare to the blend of n-butanol. The blend of n-butanol and n-octanol increased the mass fraction burn rate in the diffusion state and also increase the ignition delay of JOME from 9.9^{0}CA to 11.7^{0}CA.

However the overall outcome of engine trial and subsequent analysis of result it may be stated that the blend JOME80O20 is a better biofuel that may be used in an unmodified diesel engine. The blends of JOME and n-octanol have better performance than a blend of n-butanol and JOME while tested on unmodified diesel engine and this performance improves with increasing the percentage n-octanol up to 20 %.

LIST OF PUBLICATIONS

International Journals

1. **Sunil Kumar Sinha**, Naveen Kumar, (2019) Utilization of Blends of Biodiesel and Higher Alcohols in Small Capacity Diesel Engine, DOI: 10.4271/2019-01-0580 (Publisher: SAE Technical Paper 2019-01-0580, Scopus indexed)
2. **Sunil Kumar Sinha**, Naveen Kumar, Rajesh Kumar (2019) Characterization of the Physicochemical Property of Blend of Butanol and Octanol with Biodiesel, *DOI: 10.35940/ijitee.L3083.1081219. (Publisher: IJITEE, Scopus indexed)*
3. **Sunil Kumar Sinha**, Naveen Kumar, Rajesh Kumar (2019) Performance emission of n-octanol- biodiesel blend in diesel engine, DOI:.35940/ijrte.D7406.118419 (Publisher: IJRTE, Scopus indexed)

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

NOMENCLATURE

^{o}	Degree
^{0}C	Degree Centigrade
ANOVA	Analysis of variance
AQI	Air quality index
AV	Acid value
B100	Neat n-butanol
bBDC	Before bottom dead center
BMEP	Brake mean effective pressure
bp	Brake Power
BSEC	Brake specific energy consumption
BSFC	Brake specific fuel consumption
bTDC	Before top dead center
BTE	Brake thermal efficiency
$C_{18}H_{34}O_3$	Ricinoleic acid
CA	Crank angle
CC	Concentration for catalyst
CCD	Central composite design
CCI	Calculated cetane index
Cd	Co-efficient of discharge
CFPP	Cold filter plugging point
CFR	Cooperative fuel research
$CH_3C_6H_4SO_3H$	Para toluene sulfonic acid
CHR	Cumulative Heat Release
CI	Compressed ignition
CN	Cetane number
CO	Carbon mono oxides
Cp	Specific heat at constant pressure
CV	Calorific value
Cv	Specific heat at constant volume

D100	Neat petroleum diesel
DP	Differential pressure
$dP/d\theta$	Inside pressure rate
$dQ/d\theta$	net HRR of the inside combustion chamber
$dQw/d\theta$	rate of heat loss
EGT	Exhaust Gas Temperature
$Fe_2O_{12}S_3$	Ferric sulphate acid
FFA	Free fatty acid
FMB	Fraction of mass burn
g	Acceleration due to gravity
GC&MS	Gas Chromatography and Mass Spectrometer
GDP	Gross Domestic Product
gr.	Gram
H_2SO_4	Sulphuric acid
H_3PO_4	Phosphoric acid
HC	Hydrocarbons
HCl	Hydrochloric acid
HR	Heat release
HRR	Heat release rate
HT	Heat transfer
HV	Heating value
IC	Internal combustion
IDP	Ignition delay period
IV	Iodine value
JB	Jatropha biodiesel
JCO	Jatropha curcas oil
JO	Jatropha oil
JOME	Jatropha oil methyl ester
JOME100	100% Jatropha oil methyl ester
JOME80B20	80% Jatropha oil methyl ester and 20% n-Butanol
JOME80O20	80% Jatropha oil methyl ester and 20% n-Octanol
JOME90B10	90% Jatropha oil methyl ester and 10% n-Butanol
JOME90O10	90% Jatropha oil methyl ester and 10% n-Octanol

KB	Karanja biodiesel
Kg	Kilogram
kg/s	Kilogram/second
KO	Karanja oil
KOB	Kusum oil biodiesel
KOCH3	Potassium methoxides
KOH	Potassium hydroxides
KW	Kilowatt
LHV	Latent heat of vaporisation
m	Meter
m	mass of fuel
MJ	Mega Joule
ml	Milliliter
MOB	Mahua oil biodiesel
MR	Molar ratio
Mtoe	Million tonnes of oil equivalent
$NaOCH_3$	Sodium methoxides
NaOH	Sodium hydroxides
NBSS&LUP	National Bureau of Soil and Land Use Planning
NOB	Neem oil biodiesel
NOx	Oxides of nitrogen
O100	Neat n-octanol
OECD	Organisation for Economic Co-operation and Development
PM	Particulate matters
ppm	Parts per million
PRR	Pressure rise rate
PTSA	Para toluene sulphuric acid
Q	heat release
Q_W	Q_W is heat loss through the wall
RSM	Response Surface Methodology
RT	Reaction temperature
SV	Saponification value
T	Torque

TB	Tobacco biodiesel
TDC	Top dead center
TO	Tobacco oil
ToR	Time of reaction
WHO	World Health Organization
$ZnCl_2$	Lewis acids
Δpcj	Change in pressure rise
Δpj	Change in Pressure

CHAPTER 1

INTRODUCTION

1.1. Motivation for the Research

Copious and inexpensive energy is the biggest necessity of the present generation. The economic growth and industrialization expansion of the country depend upon the sources of energy available and the kind of technology used. However, most developing countries heavily dependent on imports of energy sources. The rapid economic growth results in an increase in the consumption of energy sources. It is well known that petroleum diesel contributes most too all energy sources due to the high efficiency of the diesel engine. However, the combustion of petroleum diesel releases harmful emissions which are dangerous for living being and environment. To resolve these problems researchers keep on developing new combustion technologies and search for alternative fuels. Some of these researches help to overcome these problems for certain extant. Out of this researches, some research suggests a change in the combustion technique. In India, CI engines are the backbone of the agriculture sector and farmers, who are not economically good. Hence modify or change in the combustion technique is not possible in India. By seeing this, these problems can only be resolved with new renewable alternative fuels and their blends. Also, the number of research has been published on the use of biodiesel and their blends as an alternative fuel for internal combustion (IC) engines. However, some of these fuels reduced the performance and increasing NO_X emissions of the engines. Further, after exhaustive study, it is found that most of the work in this area is concentrated on binary blend and lower alcohol only. Also, the blending of biodiesel is concentrated on petroleum diesel.

To overcome the two biggest problems of increasing air pollution and the heavy burden of importing crude oil on the economy it becomes necessary to work for a completely renewable alternative for petroleum diesel. This time the world is suffering from economic crises. India is also one of these countries. Hence it is the right time to work in this direction effectively and make the country self-sustained in terms of crude oil. It is well known to all that inexpensive and economical sources of energy act as blood to the growth of the country. Also, cleaner fuel help to achieve a better environment and air for the future.

1.2. Energy Crisis:

The economical energy requirement is the biggest challenge for almost all countries, especially faster developing and developed countries. As these countries don’t have sufficient energy resources hence they totally depend on the import of fossil fuels [1], [2]. Which is the biggest burden on their economy. It is predicted that presently the world is at a peak rate of fossil fuel production and consumption, which is causing unprecedented perturbation in the prices [3]. From the study conducted on the energy scenario of the World, the consummation of primary energy for the globe is predicted to be 19275 million tonnes of oil equivalent (Mtoe) in 2050 which was 13761 in 2016 Mtoe [4]. The rate of increasing consumption is around 1.4 times. However, the rate consumption of primary energy sources decreases from 1.4% to 0.8% between the years 2011 and 2016. This is because of the decreasing rate of Organisation for Economic Co-operation and Development (OECD) countries [4]. The decreasing rate of consumption of primary fuels for OECD countries is faster than the overall decreasing rate. Presently the USA is the largest consumer of the primary source of energy and fossil fuels. China will surpass the USA in next 10 years and become the largest consumer of primary energy sources and fossil fuels by 2030 [5]. The rapidly growing economy of India also required a very large amount of energy. Hence, it can be predicted that the primary energy consumption of India becomes equal to China by 2050 [6], [7].

As discussed earlier, India is one of the fastest-growing country hence energy requirements are also very high. But India has very poor resources of crude oils. Therefore, India is totally dependent on the import of fossil fuels from other countries like Nigeria, Iraq, etc. India imports nearly 80% of total petroleum products to full fill its energy requirement. The crude oil consumption in India increases by 53% from 2008-09 to 2017-18. The total consumption of crude oil in India was 170.58 million tonnes during 2008-09 which increased to 260.83 million tonnes in 2017-18. On the other hand, the out-turn of dark oil in India increased to 40.4 million tonnes in 2017-18 which was 37.8 million tonnes in 2008-09 [8]. From the data, it is found that the increase in the production of dark oil in India is increased only by 6% from 2008-09 to 2017-18. It is calculated that India spends nearly ₹1.4 lakh crore in importing crude oil for the fulfilment of its energy requirement. The quantity of crude oil production and consumed from 2008-09 to 2017-18 by India is shown in figure 1.1:

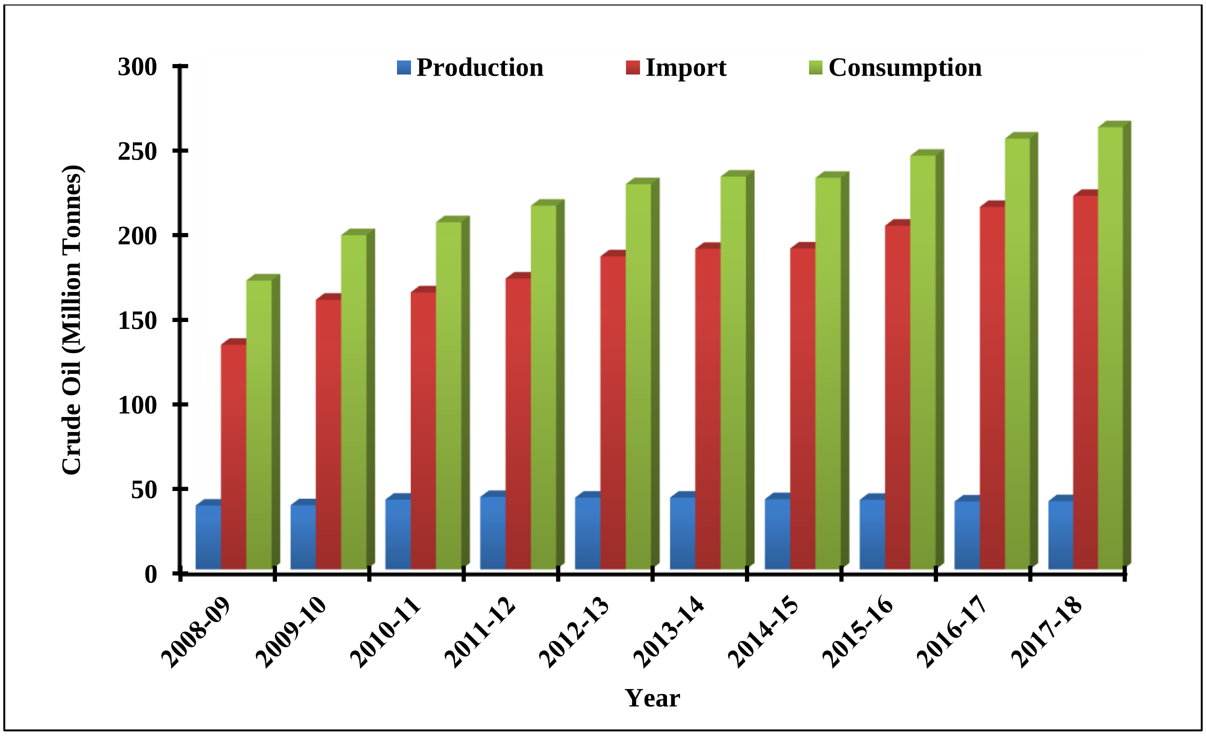


Figure 1.1: Crude Oil stats of India

It is clearly seen from the figure that the dark oil out-turn is almost stagnant in India while the consumption is increasing continuously. The net dark oil coming in enhanced in India from 132.78 MT to 220.43 MT during 2008-09 to 2017-18. The domestic expenditure of dark oil in India is upsurge because of its high demand in transportation, agriculture, power generation, and industry sectors. The sector-wise crude oil consumption is shown in figure 1.2. The transportation sector is the largest consumer of crude oil followed by industry, agriculture, and power generation. This indicates that the power generation sector still believes in the use of coal. Also in petroleum products, petroleum diesel comes in the top list of consumption because of the higher efficiency of diesel engines due to the high compression ratio. Diesel engines produce more power with higher efficiency which makes it an ideal engine for transportation, agriculture, and industry sectors. It is found that the consumption of petroleum diesel in India is nearly four times than gasoline [9].

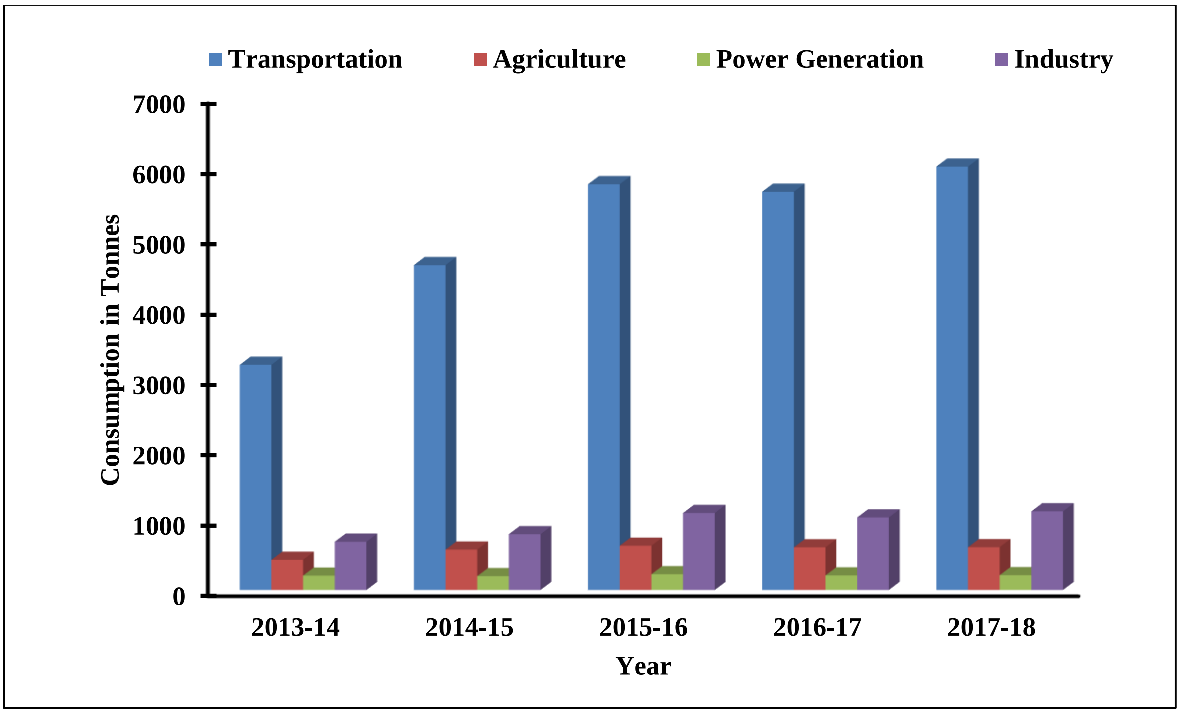


Figure 1.2: Sector-wise crude oil consumption

1.3. Air Pollution & Climate Change

Air pollution is increasing day by day and going toward a severe level. The air quality in most of the metro cities in India reaches the dangerous mark. Several times in a year, the air quality index (AQI) of Delhi goes to a hazardous level. Due to this every year in the month of November to next year January, the Delhi government applies the odd-even number rules on the private vehicles. The transportation, agriculture, and industry sectors are playing a big role in this air pollution.

The emissions released due to combustion of fossil fuels like petroleum products, coal, CNG, etc. is the biggest contributor to air pollution. The combustion of all these fuels released harmful emissions like particulate matters (PM), oxides of nitrogen (NO_X), carbon dioxides (CO_2), carbon mono oxides (CO), etc. which are the major portion of polluted air. All these emissions cause severe health issues to the human body especially new born babies and old peoples. According to one report released by world health organization (WHO), around 90% of climate change diseases and almost 40% of air-related diseases are borne by children of age less than 5 years [10], [11]. These diseases include behavioural development, adverse birth outcomes, respiratory illness, childhood cancer, and impairment of cognitive, etc. [12]. However, these effects are not so visible up to now but in the future, these effects become more aggressive. Further, these problems will be more in developed and rapidly developing countries as they are using more fossil fuels to fulfill their energy requirements. Apart from these health problems, harmful emissions are also responsible for climate change.

Continuous increasing content of CO_2 in the air increases the greenhouse effect as CO_2 is the main gas for the greenhouse effect. In the USA, 81% of greenhouse gas is contributed by CO_2 out of that 90% is released by the combustion of fossil fuels [13]. The concentration of CO_2 in the air is increasing regularly due to the combustion of fossil fuels for the fulfilment of energy requirements. Almost all fossil fuels contain carbons that release CO_2 after complete combustion [14]. The trend of concentration of CO_2 in the atmospheric air is shown in figure 1.3. The concentration of CO_2 in the atmospheric air is continuously increasing year by year. As per the report released by NOAA and American Meteorological Society, the CO_2 concentration in atmospheric air reaches 407.4 ppm in 2018 which is 2.5 ppm more than 2017 value [14], [15]. This results in an increase in the average temperature of the earth as CO_2 can absorb the thermal radiation, heat from the sunlight, and reflected by the earth. However, CO_2 is the least harmful among other greenhouse gases like methane, nitrous oxides, CFC-11, CFC-12, and other minor gases. But its quantity is much higher in the atmospheric air as compared to other greenhouse gases.

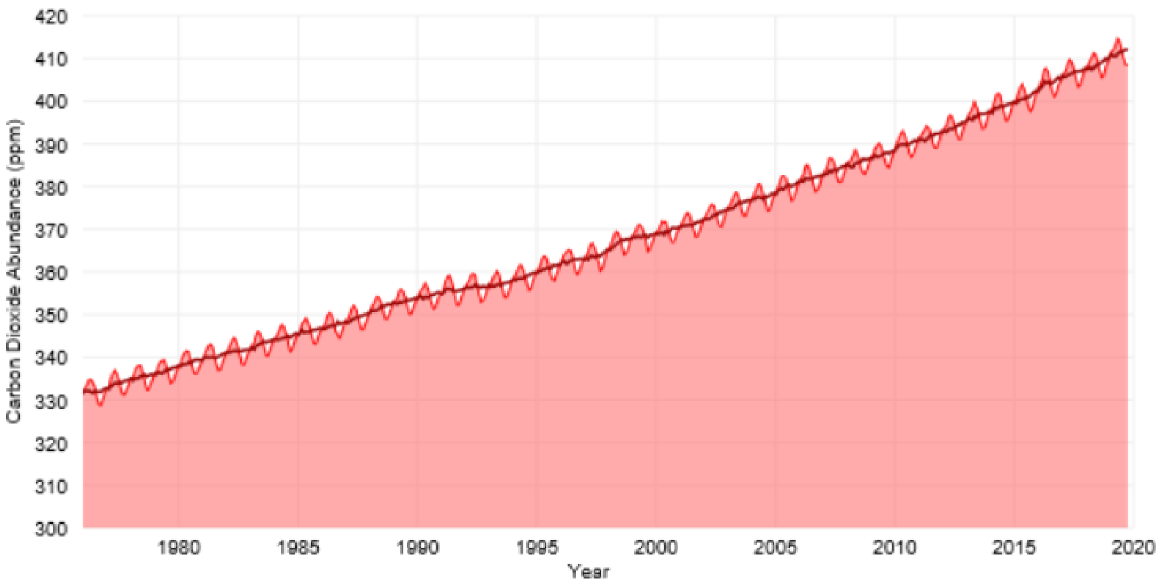


Figure 1.3: Trend of CO_2 concentration in atmospheric air [14].

Further, CO_2 absorbs less radiation and heat than other greenhouse gases but it is more copious and remains for a longer period in the atmosphere. Due to this, the atmosphere absorbs 3 watts extra solar radiation per square meter which comes to earth [14], [16]. Hence, the earth's temperature is increasing continuously. “That additional hotness is guiding local & periodic temperature immoderations, dropping snowflake shelter & sea ice, escalating dense rainfall, & changing dwelling spectrum for plants and animals - exploring some & reduction others”[17]. The variation in the surface temperature of the earth since 1880 is shown in figure 1.4.

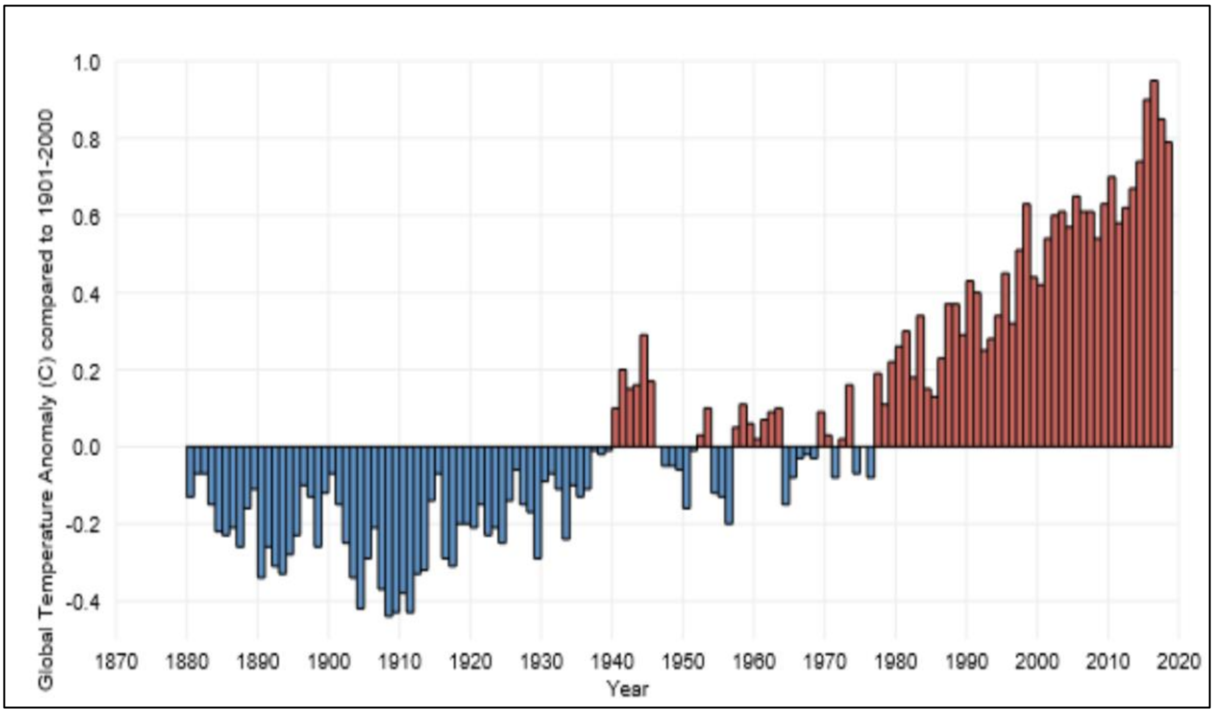


Figure 1.4: Memoir of average temp. of the earth [17].

Hence a definite solution for both severe problems of the energy crisis and air pollution and climate change is urgently required. The number of researchers worked in this direction and concluded that biodiesel and other renewable alternative fuels are the best and effective solution for the problems discussed above [9], [18]–[23].

1.4. Policies on Bio-Fuel in India

The crude oil price in the international market keeps on fluctuating. Such fluctuation in crude oil prices becomes the biggest worry to the world economy especially the fastest growing countries. In India, road transport accounts for 6.9% of total Indian gross domestic product (GDP) [24]. “At present, diesel lonely commingle projected 72% of vehicular fuel requisition trailed by petrol who’s contribution is 23% only and rest by supplementary fuels including other gaseous fuels and petition of these fuels growing constantly” [24]. Indian economy remains permeable until unless the substantial indigenous alternative to the petroleum fuel is not sublime [25]. Therefore, the Indian government set a target of reducing 10% of crude oil imports by 2022 [24]. In this regards government makes five important strategies that include, “Aggregate Local out-turn, Accepting biofuels & natural sources having the capability to being renewed, Energy mightiness Customs, Enhancement in Refinery Procedures & Requirement Replacement”[24].

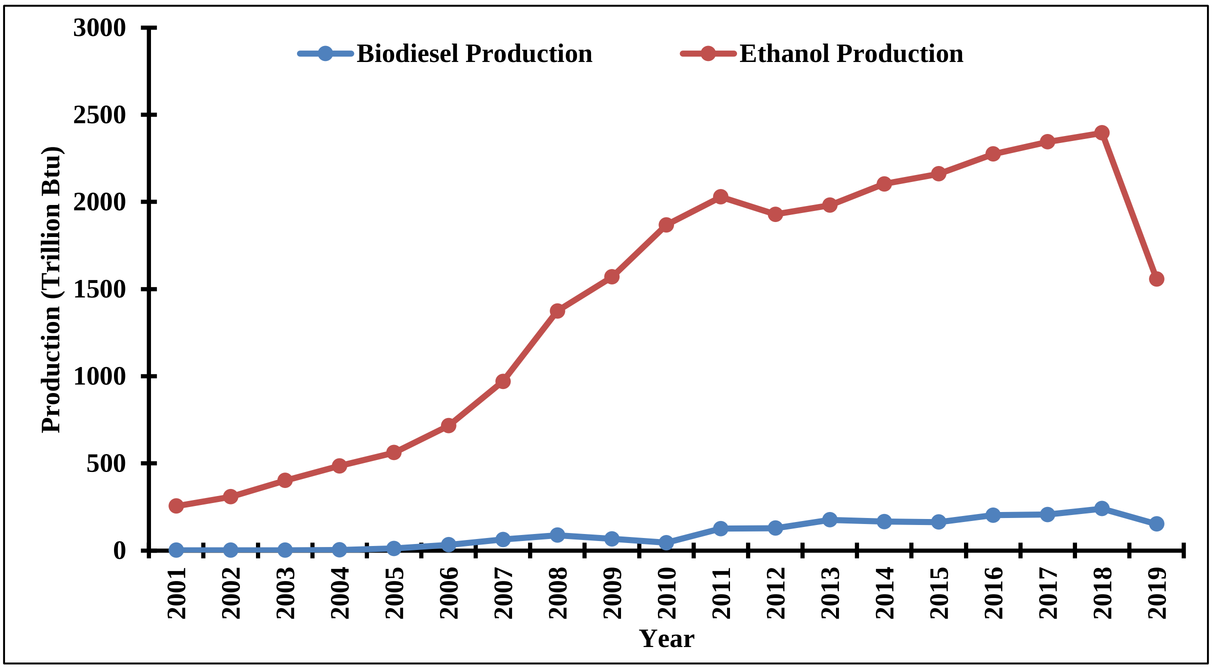
For fulfilment of commitment, the government of India launches a program by which the trees of Jatropha and Pongamia are planted around 11000 acres of area in 2014 [26]. Some of the trees died due to improper nurturing and lack of care. But other trees are mature enough and have a good production rate. Apart from that, the Government of India also plans to produce biodiesel from waste plastic oil, waste cooking oil, and waste biomass. The present government fixes the goal of increasing the blending of ethanol in gasoline to 20% which is 2% at the present and blending of biodiesel in petroleum diesel to 5% which is less than 0.1% at present by [24]. For that achievement the government of India set some goals which are [24]:

a) Effective use of already existing feedstocks and develop new feedstock.
b) Emphasising the ongoing supply of ethanol and biodiesel.
c) Develop an advanced technology for biodiesel conversion.
d) Upgrading the bio refineries to the second generation.
e) Aware the peoples for utilising the blended fuel with biodiesel and ethanol.

However, biodiesel is showing its growth in the last few years due to again increase in charge of dark oil in the international market, organising environmental events, government policies on biodiesel and understanding the responsibility for the future [26]. Therefore, most of the countries gradually and partially moving for adopting biofuel like biodiesel and ethanol as a replacement for petroleum fuel. Further, to increase the production and consumption of biofuels some countries like Brazil, the US, Australia, and Argentina, etc. launches some schemes and offers [27]. Some of very interesting and important are discussed as [27]–[29]:

- Tax credits
- Mandatory use and blending
- Trade restrictions.

This results in the enhancement of biodiesel and ethanol production in these countries and other countries as well. The trend of ethanol and biodiesel production is shown in figure 1.5.



*data up to August 2019

Figure 1.5: Year-wise production of Biodiesel and Ethanol [30]

The legitimate about biodiesel in India have also become stronger which never happen earlier [26], [31]. Therefore, biodiesel production and consumption in India increasing gradually. Presently India comes at 26th rank in biodiesel production worldwide which was very poor some time back [32]. However, the major biodiesel production feedstocks are limited to palm oil, jatropha, algae, rapeseed, sunflower, canola, and soybean oil. Hence, it can be said that biofuels are mainly categorising into two categories i.e. biodiesel and bio alcohol.

STRUCTURE OF THESIS

This thesis comprises five chapters which are briefly described below. The structure of the chapters is as follows:

CHAPTER 1: (INTRODUCTION)

This is an introductory chapter that gives an overview of the present research. The chapter starts with the motivation of the research and describes why this topic of research was selected. This chapter deals with the problems facing by India and the world at present. These problems include energy crises, air pollution, global warming, and the future of energy. Apart from it, this chapter also highlights the scope of biofuels especially biodiesel and alcohol as alternative energy sources for internal combustion engines. The policies made by different countries to boost biofuel production are also given in this chapter.

CHAPTER 2: (LITERATURE REVIEW)

This chapter mainly deals with the review of the literature. It reviews the importance of diesel engines in the Indian economy. In this chapter, the alternative fuels (like biodiesel and alcohol) for diesel engines are also reviewed with their compatibilities, availabilities, and future perspectives. The properties of different biodiesel and alcohol are also reviewed in this chapter. The combustion behaviour of most of the biofuels is also discussed in this chapter. Apart from this the performance and emission characteristics of diesel engines using different biofuels also reviewed in this chapter. At last, the research gap problem statement and objective of the study are emphasised.

CHAPTER 3: (SYSTEM DEVELOPMENT AND METHODOLOGY)

The methodology of the present research is explained in this chapter. This chapter includes a selection of feedstock for biodiesel production, system development for biodiesel production, optimisation of the biodiesel production process, selection of alcohol, and blend preparation. This chapter also explains the methodology for testing the physicochemical properties of tested fuels. Also, the methodology of analysing the combustion, performance, and emissions characteristics of a diesel engine using different test fuels is explained in this chapter.

CHAPTER 4: (RESULTS AND DISCUSSION)

This chapter contains all the results obtained in the present research work. The results of all physicochemical properties of all tested fuel and the analysis of these properties with petroleum diesel fuels are presented in this chapter. Also, the results of the testing of all tested fuels on the direct injection diesel engine and a comparison of the results obtained with baseline data are done in this chapter.

CHAPTER 5: (CONCLUSION)

All the major findings during the present research are given in this chapter. Also, the scope of future work is also given in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Most of the energy requirement is full fill by crude oil which becomes the biggest concern for the world, as fossil fuels are diminishing at an alarming rate [18]. Therefore most of the researchers are working to find out the renewable alternative to fossil fuels. The present work is also dedicated toward determining the renewable and cleaner substitute of petroleum diesel which is the most consumed form of fossil fuels after coal. In this chapter, the exhaustive literature has been done for finding the alternative to the petroleum diesel in all respect. Therefore, the literature review has been done for the most convenient alternatives to petroleum. While doing the literature, more than two million small capacity diesel engines that are currently operating in India also considered. In this chapter, a few very attractive nonedible feedstock of biodiesel are reviewed exhaustively to treasure exquisite feedstock for the current research. The literature survey also performs dedicatedly to quest the most effective renewable alcohols which patronage to mend the properties of biodiesel.

2.2. Role of CI Engines in Development of India

Energy is the principal necessity of the development of any country and the country having sufficient energy springs has more chance to grow with a faster rate[22], [33], [34]. However, the availability of energy resources is not the only parameter to describe the speed of development, the technologies practiced to utilised that energy is also equally important [35]. Generally, the engines are utilized to convert the chemical energy of fossil fuels into other useful forms. At present, the internal combustion engine is more popular than an external combustion engine due to its compact size and lightweight. These properties of the internal combustion engine make it the first choice for transportation and agriculture sectors. Among internal combustion engines, the compressed ignition (CI) engines are gaining popularity due to their higher compression ratio and higher rated power. Apart from this, the efficiency of CI engines is also higher than spark-ignition engines [36]. Which makes it very popular in the agriculture sector. In India, more than Two million of stationary engines are used for irrigation in rural areas as continuous electricity supply is the biggest challenge in rural areas. Also, all these properties of diesel engines make it popular in the transportation sector and power generation. This leads to higher petroleum diesel consumption in India, at present the petroleum diesel consumption is around four times than gasoline consumption in India [34]. Due to the above mentioned properties, most of the goods transport vehicles and passenger vehicles are powered by diesel engines only. For the growth of industries the product need to transport from one place to another where that diesel engine plays a very crucial role. However, with higher efficiency and higher capacity of diesel engines, these engines are associated with higher exhaust emissions as well. More than 80% of total air pollution comes out from the vehicles is emitted by diesel vehicles only. This is one of the biggest challenges in front of researchers. Also rapidly depleting fossil fuel reservoirs is another big encounter for them.

2.3. Alternative Fuels for Diesel Engine

It is very much possible that diesel engines can be run on other alternative fuels as the first time the diesel engine was run on peanut oil by Sir Rudolf Diesel. So the use of alternative fuels in a diesel engine is not a brand new technology. Also, the continuously increasing demand for fossil fuels all over the world to fulfil their energy requirement coupled with limited availability and increasing air pollution forced the researchers to work in the direction of renewable alternatives for fossil fuels. As discussed above that the higher emissions of diesel engines and utilization of mostly petroleum diesel only for fuelling it become the biggest encounter for the researchers to put the effort in that direction. Therefore, the number of research is steered to quest alternative of petroleum diesel but till now the replacement of diesel is not found. Moreover, the researchers found some alternatives like waste plastic fuel, liquefied biogas, alcohols, and biodiesel, etc. some of them render benignant results while tested on diesel engines but several fail to achieve requisite results. Selected fuels can be used directly in diesel engines because their properties are quite similar to petroleum diesel however rest cannot be used directly due to their properties like higher density, viscosity, and lower cetane number, etc. Alternative fuels like waste plastic fuel have good properties but still under contemplation due to the complicated production process and government policies on waste plastics. Further, the liquefied biogas fails to generate interest in the researchers and industrialists due to complexity in the generation, poor heating value, and higher exhaust emissions. On the other hand, alternative fuels like biodiesel and alcohol are gaining interest among researchers, and the same is reflected in government policies. Unfortunately, none of them can use directly as a fuel for unmodified diesel engines because of their properties. Most of the biodiesels have higher kinematic viscosity and density than normal diesel fuel and all existing diesel engines are designed by keep properties of diesel in mind. Opposite to this most alcohol has nearly similar or better kinematic viscosity and density compared to diesel but the heating value and cetane number of most of the alcohol are the biggest barriers for them. However, both of these fuels are showing better results when blends with diesel. After going through the number of research articles it is found that most used alternative for diesel engines are:

- Biodiesel
- Alcohols
- Waste plastic fuels
- Compressed natural gas

The biodiesel and alcohols are the most used alternative fuels in the literature and also showing better results among all. However, till now it is impossible to replace petroleum diesel completely but the work is going on in this direction.

2.3.1. Biodiesel

The use of biodiesel as an alternative fuel is not the recent discovery. The work on biodiesel starts when a small diesel engine discovered which can run with various kinematic viscosity and density oil. The use of low density vegetable oil in engines started during world war-II [37]. The latest research was patented in 1977 by Brazilian scientist Expedito in which the scientist produce biodiesel [38] through the industrial process which is commonly known as transesterification. However, the first patent on a compressed ignition engine was registered by sir Rodulf Diesel in which he runs his invented engine on vegetable oil using a large fuel injector to overcome the problem of cocking [39]. The interest in biodiesel production increases with time all over the world. Therefore, almost all countries which do not have sufficient sources of energy are working to find the alternative and renewable source of energy for fossil fuels. The biodiesel is an auspicious option in this direction. The renewability of biodiesel is revealed in figure 2.1.

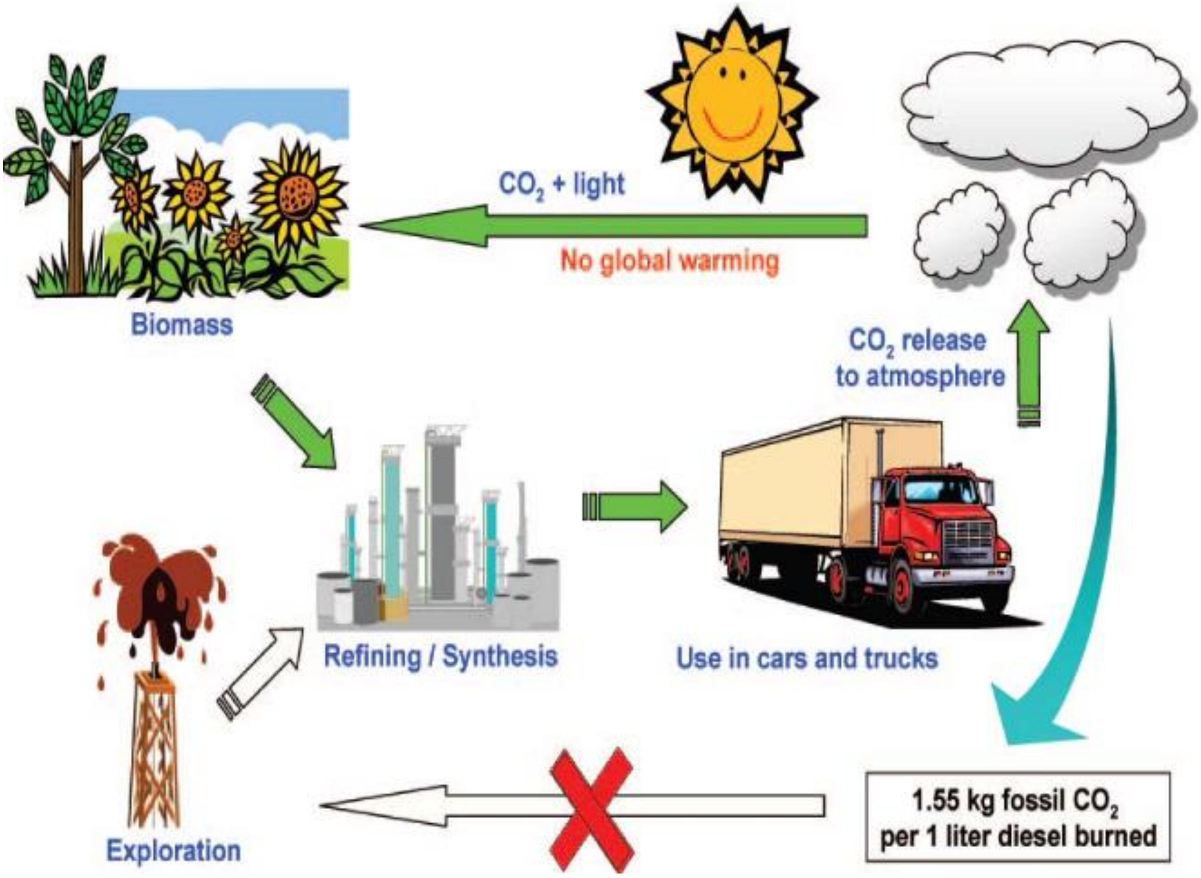


Figure 2.1: Comparison of biodiesel & diesel for CO$_2$ emissions.

The biodiesel is a long chain of fatty acid alkyl esters which generally produced by the transesterification process [40]. The biodiesel can be produced from any vegetable oil (edible and inedible), animal fat, waste cooing oil, waste lubricating oil, etc. through the transesterification process [3], [40]–[42]. During the transesterification process, the triglyceride reacts with alcohol in the presence or without the presence of catalysts at a suitable time and form fatty acid alkyl esters and glycerol. The presence of catalyst enhances the rate of the chemical reaction. The temperature and agitation speed also affect the rate of reaction process [43]. The properties of most of the biodiesel are very comparable to diesel fuel which makes it famous as diesel fuel replacement [44]–[46]. However, some of the biodiesel has higher kinematic viscosity which becomes a hurdle for utilizing 100% biodiesel [47], [48]. The biodiesel also contains free oxygen which enhances the combustion properties of fuel [49]–

[51]. As discussed above most countries that do not have sufficient energy sources are working on biodiesel production. They are introducing attractive policies for producers and consumers which help to increase the production and consumption of biodiesel. Some of these policies already discussed in chapter 1.

The countries like United States of America, Indonesia, Argentina, Brazil, etc. are implemented such policies. And those policies also showing results and the total consumption and production of biodiesel increase in these countries during the last few years. The feedstocks for biodiesel production are different for different countries depend upon the availability of oil/fat. For example, in Indonesia, and the USA the production of palm oil is very high so these countries are producing biodiesel from palm oil. In developing nations like India where edible oil is not sufficient for eating therefore these countries must not make biodiesel from any virgin edible oil. Hereby Indian government is planning to utilize inedible feedstock like karanja, mahua, pongamia, jatropha, etc. for biodiesel production which can be cultivated in the wasteland. Indian government work in that direction and also took steps to implement the blending of biodiesel in diesel fuel. Similar to that various countries took a number of steps to enhance the production of alternative fuels. After seeing all these steps taken by various countries it is very straightforward to understand that the scope and future of biodiesel are quite bright. In countries like India, the potential of biodiesel production is higher than in other countries as it imports nearly 70-80% of crude oil to fulfil its energy requirement.

The consequences of utilising biodiesel in an unmodified diesel engine are also pretty impressive. The biodiesel generally contains 5-15% of free oxygen which makes combustion of biodiesel a little smoother than mineral diesel [48], [52]. The cetane number of most of the biodiesel feedstocks are better or comparable than diesel which is the basic necessity of fuel for diesel engine [53]. Biodiesel is produced from oils or animal fat therefore it is completely renewable. Also, biodiesel is free from toxic materials and can be stored easily as it is non-flammable at room temperature. Most biodiesel is produced from vegetable oils so the carbon emissions are nearly zero as the plant consumes the nearly same quantity of carbon dioxide which is released during the combustion of biodiesel. The comparison of all properties range for biodiesel and diesel fuel is an exhibit in table 2.1.

Table 2.1: Compression of various properties range for diesel & biodiesel [54]–[58].

Property	**Diesel**	**Biodiesel**
Standard	ASTM D975	ASTM D6751
Composition	C10-C12 HC	C12-C22 FEME
Density (kg/lt^3)	0.85	0.86-0.9
Kinematic viscosity (mm^2/s at 40°C)	1.3 - 4.1	1.9 – 6.0
Boiling point (°C)	188 – 343	182 - 338
Cloud point (°C)	-15 to 5	-10 to 17
Flash point (°C)	60 – 80	100 – 180
Pour point (°C)	-35 to -15	-15 to 10
Cetane Number	44 – 55	48 - 65
Stoichiometric ratio (Air to Fuel ratio)	15	13.8

In rural areas, peoples are facing the problem of shortage of electricity supply and transportation of petroleum product supply. The biodiesel can play a crucial role in their development during such conditions [59]. The farmers can run their agriculture instruments and irrigation pump with biodiesel. Also due to its renewability directly or indirectly it serves climate change and helps in reducing air pollution. Biodiesel production does not require drilling, exploring, and distillation process which consumes more energy. Biodiesel is produced through the transesterification process which is very simple and less time-consuming. Therefore, the cost of biodiesel production is also very reasonable because very basic chemicals are required during the transesterification process. Therefore the cost of biodiesel is depended upon the cost of feedstock used to prepare biodiesel. In the rural area, the farmers can plant trees on the fences of the field and the oil extract from their fruits can be plied for biodiesel production. The farmer can prepare biodiesel as per their requirement because biodiesel production required very little time. If oil production is higher, the farmers can prepare more biodiesel and sold it to the market and can generate some revenue and employment as well.

After going through the number of literature the following benefits and shortcomings of biodiesel are noticed:

Benefits:-

- Biodiesel is one of the optimum solutions for the renewable alternative of diesel fuels, air pollution, and climate change.
- The biodiesel has a higher cetane number and oxygen content which improves combustion physiognomies and makes it better fuel.
- Most of the biodiesels have lower ignition delay than petroleum diesel.
- The biodiesel is prepared from vegetable oils and animal fat which make it renewable and help in improving climate problems.
- The biodiesel is prepared though the transesterification process which is less time consuming, easy and economical as well.
- The biodiesel has a higher flash point generally more than 100°C this makes it safe for storage and transportation.

- Biodiesel has superior lubricating properties. Therefore biodiesel helps in reducing wear tear of the engine, injection pump, and nozzle that improve the performance and life of an engine.
- The utilisation of biodiesel reduces the dependency of imported crude oil and strengthening the nation economically.
- The use of biodiesel in diesel engines leads to reduce particulate matters (PM) by 50% also it reduces the emissions of hydrocarbons (HC) and carbon monoxides (CO).
- The biodiesel is renewable and biodegradable in nature.

Shortcomings:-

Although biodiesel has a number of advantages due to its renewability, properties, and combustion ability which make it promising fuel for diesel engines, there are some limitations which are the main hurdles on the way to the commercialization of biodiesel. These disadvantages or limitations are as follows:

- The higher content of oxygen in biodiesel leads to higher NO_X emissions especially at higher load which is one of the main problems of biodiesel. However, there are several methods for reducing NO_X emissions such as changing the injection timing, using a catalytic converter, and exhaust gas recirculation.
- The heating value of biodiesel is generally 10-15% lower than petroleum diesel which increases the overall fuel consumption and results in lower brake thermal efficiency.
- Biodiesel has lower oxygen stability which might be harmful to the engine components.
- The biodiesel has higher kinematic viscosity which may cause cocking in fuel injector, poor atomisation, and cylinder deposits when used 100% biodiesel. This leads to a decrease in the life of fuel injector and engine.

- Worldwide, 80% of biodiesel is prepared from the editable vegetable oil due to its lower FFA which might cause a problem in food security.
- The oxygen content in biodiesel might cause corrosion problems in some of the engine parts.
- The biodiesel is soluble with lubricating oil which decreases the overall lubricating properties of the lubricant. Therefore the lubricating oil needs to change frequently while using 100% biodiesel in a diesel engine.
- The biodiesel has a higher CFPP temperature compare to petroleum diesel which might results in a conversion of biodiesel into the gel at a lower temperature. This is not the desirable property for any fuel at lower climate temperature conditions.

2.3.2. Alcohol

In the starting, the alcohols are used as the main reactants and solvent for industrial purposes only. However, from the early 1900's the basic alcohols like methanol and ethanol are starts using as fuel in heat engines due to their properties. These alcohols are used as fuel for a longer time of period, however, these are associated with some problems like lower heating value and cetane number. Therefore the use of 100% alcohol as fuel in the internal combustion engine gradually reduces. The properties of these alcohols are still confusing researchers and they use ethanol as an additive for gasoline. The ethanol has a higher octane number which reduces the knocking tendency of gasoline. This results in very limited work on alcohols used as fuel for the diesel engine. The reason for that is the lower cetane value of alcohol which limited the work of alcohol on the diesel engine.

The renewability and properties of alcohol generating interest in the researchers again due to continuously decreasing the level of energy sources and rapidly increasing air pollution. This interest results in the exploration of higher alcohols as well. The researchers explore higher alcohols like butanol, propanol, octanol. The number of researches has been conducted on the above discussed alcohols as fuel and the results are found very attractive. However, the main attraction of alcohol is its renewability. The alcohols can be prepared in industries as well as the local level. However, it is not possible to prepare all alcohol at the local level. The process used to prepare alcohols are as stated below:

- Fermentation, methanol, and ethanol are generally prepared through this method. This method can be used at the local level or industrial level.
- Synthesis, during this process the alkene and water react with each other in the impendence of acidic catalyst and produce alcohol.
- Catalytic synthesis, mainly higher alcohols are prepared through this method. In this process, the syngas is passed over suitable catalysts to produce the required alcohol.

The main alcohols which found suitable as fuel for internal combustion engines are methanol, ethanol, propanol, butanol, and octanol.

Methanol

Methanol is the first member of the alcohol family having chemical formula CH_3OH. The methanol is also known with the name of wood alcohol and methyl alcohol. The name wood alcohol comes as it was prepared from wood sometimes. However these days it is prepared from carbon monoxides, carbon dioxide, and hydrogen in the industries [60]. Further methanol is also prepared from natural gas and coal effectively in the industries [61]. The methanol is colour less, light, flammable, and volatile alcohol. However, methanol is highly toxic in nature and generally used as fuel, antifreeze agent, and solvent. The methanol is the most used alcohol for the transesterification process.

Methanol is also prepared from renewable biomass which makes it renewable and green fuel for the internal combustion engine. The properties like oxygen contents, higher octane number, low flash and boiling point with easily dissolve in gasoline and diesel make it attractive additives for the fuels. The use of methanol as an additive for gasoline help in reducing NO_X and PM emissions from the SI engines [62]. The use of alcohol in the diesel engine also helps in decreasing the soot, particulate matter, NO_X, and smoke of diesel engines as well [63]. On the other hand, methanol is also used as fuel for fuel cells and performing well as compared to other liquid fuels [64].

Ethanol

Ethanol is another simplest form of alcohol represents with chemical formula CH_5OH. The ethanol is produced naturally from the sugars cane, waste grains, wheat, etc. through fermentation processes in the presence of yeast [65]. Therefore the ethanol is nay recognized as ethyl alcohol, drinking alcohol & grain alcohol. The ethanol is a flammable, volatile, and colourless liquid. However, it is not toxic in natural as methanol. Due to its properties, it is used as antiseptic and disinfectant. Ethanol is used for drinking and also used in the number of medicines. The properties like higher octane number, good heating value, and impressive density make ethanol a good alternative fuel for internal combustion engines [66]. The higher octane number of ethanol makes it a good additive for gasoline. The addition of 5 to 10% of ethanol decreases the knocking tendency of gasoline without changing the heating value much. However, the problem with the solubility of ethanol with gasoline and diesel at higher concentrations is the biggest issue in increasing the percentage of ethanol in blends [67]. The highest use of ethanol is in the form of fuel or as an additive to the fuel due to its properties only [68].

Propanol

Propanol is one of the rarely discussed alcohols among all alcohols. The propanol comes with three carbon chains having chemical formula C_3H_7OH [69]. Usually, propanol comes with two isomers: 1-propanol also known as n-propanol, and 2-propanol also known as i-propanol [70]. Both the isomers are used as a solvent for industrial purpose. Propanol is prepared through the fermentation process however the production is very less which makes it costly alcohol [71]. Similar to methanol and ethanol propanol is also colourless and odourless alcohol. In terms of toxicity, propanol is less toxic than methanol. As discussed earlier the propanol is used as a solvent for many industries which includes rubber, surface coating, pesticide, cosmetics, ink, and textile, etc. [71].

The number of researchers researched propanol and use it as fuel for spark ignition and diesel engine. The higher octane number of propanol makes it good fuel for spark ignition engines in terms of knock resistance [52]. However, the calorific value of propanol is much lower than gasoline which leads to a decrease in the BTE of spark ignition engine. Therefore propane can be used as an additive for the gasoline to improve the anti-knocking index of gasoline [72]. Other properties of propanol like heating value, cetane number, self-ignition temperature, etc. are better than methanol and ethanol [73]. These properties of propanol attract research to use it in a diesel engine as well. However, the calorific value and cetane number of propanol are much poorer than petroleum diesel which is the biggest challenge for the researchers. The propanol has oxygen content which helps in better combustion at higher load. The addition of propanol with diesel leads to a decrease in NO_X, PM, and soot emissions [74]. After having better properties than methanol and ethanol, propanol is not widely explored due to its higher coast and slow productivity.

Butanol

Butanol comes in the category of long chain alcohols as it contains four carbon atoms connected with other hydrogen and oxygen atoms [75]. The chemical formula for butanol is C_4H_9OH. The four carbon atoms of butanol are forming a straight chain like structure. The butanol comes with four isomers named as n-butanol, 2 stereoisomers of sec-butanol, iso-butanol, and tert-butanol. However, among all isomers, only two i.e. n-butanol and iso-butanol have better properties as fuel [76]. Butanol can be manufactured from agriculture crops so that it is classified as a green fuel. The calorific value (CV) and cetane number (CN) of butanol are more than lower alcohol i.e. methanol and ethanol. The water affinity property of butanol is very low which permits it to simply mix with gasoline and diesel.[77]. However, the butanol production technologies are not so efficient and economical some time back because researchers were not concentrating much on butanol. But continuously increasing demand for energy and increasing pollution levels force the researchers to work on butanol [78]. Butanol can also be prepared from petroleum, this butanol is also known as petro butanol. Similar to other alcohols, butanol is also used as solvents in various industries. Also, the butanol is used as alcohol for esterification and transesterification process. However other properties like better cetane number, higher energy content, and better ignition quality of butanol make it better fuel for internal combustion engines [75].

Various research has been published by the number of researchers in which they used butanol as fuel for both spark ignition and compression ignition engines [75], [79]–[83]. The research shows that the performance of diesel engines improves when 20% of butanol mixed with petroleum diesel. However, a further increase in the percentage of butanol put some adverse effect on the performance of the engine [75], [80], [84]. This improvement is due to the oxygen content in the butanol which improves the combustion characteristics of blended fuel at higher load. The blend of butanol with diesel fuel also leads to a decrease in exhaust emissions of the diesel engine. However, some emissions like hydrocarbon increase slightly [85]. The butanol is used in spark ignitions engines prior to diesel engines. The performance of butanol is better in spark ignition engine than previously discussed alcohols.

Octanol

Most of lower carbon alcohols are used as fuel for spark ignition engines due to their high octane number. The cetane number of lower carbon alcohols is very low as compared to petroleum diesel. Therefore this restricts researchers to use these alcohols for compression ignition engines. In this scenario, octanol found a good selection of researchers for diesel engine fuel. the cetane number of octanol is much higher than methanol and ethanol also the heating value of octanol is higher than these alcohols and comparable to petroleum diesel [86]. Octanol is higher carbon alcohol represented with chemical formula $CH_3(CH_2)_7OH$.

The use of octanol as fuel for diesel engines started recently by the researchers. The results quoted by the researchers are pretty impressive and attractive as well [45], [87]–[89]. In the initial stage of octanol production, octanol is used to produce in industries through chemicals and other alcohols and mostly used in perfumes and cosmetic products [90]. Once the properties of octanol were tested and found impressive as fuel and the researchers start working on it as an additive and as the main fuel, the producer starts working on alternative methods of octanol production. Previously, two main methods of octanol production in one method ethylene is reacted to triethylaluminum and in second method octanol is produced from n-heptane through an oxo synthesis process. Both these method contributes to the largest production of octanol [91]. Later, the primary octanol such as 1-octanol is started producing from biomass with the help of various catalysts [91]–[93]. This method expansion its attractiveness in a very petite period of time due to the utilisation of biomass. After that researchers claim octanol as bio alcohol.

2.4. Feedstocks for Biodiesel Production

Biodiesel can be produce from any type of oil and fat through various converging technologies. Almost 350 types of various oils and fats are already identified from which biodiesel is produced [94]. The cost of biodiesel depends upon various factors like the cost of feedstock, the process used, chemicals and labour. However, the cost of biodiesel mainly depends on the cost of feedstock. The preferred feedstock for biodiesel production varies from country to country even region to region as well with in the country. This feedstock is selected on availability, cost, weather condition, agricultural activities, and geographical location of the country [95]. Like in Malaysia and Indonesia, the production of palm oil is highest in the world. So most of the work published in these countries on biodiesel produced from palm oil only. In India, the coconut oil is produced at a larger scale in the south region so the feedstock is found coconut oil in most of the research works [96], [97]. In the northern region of India most work is concentrated on jatropha, mahua oil [18], [98]. The estimated cost distribution among all parameters for overall biodiesel cost is shown in figure2.2.

The biodiesel feedstock is broadly classified into four categories all are exhibit in figure 2.3. The use of vegetable oil starts with the invention of diesel engine however the use of biodiesel start after a long time. Some researchers produced biodiesel from edible oils obtained from the trees like palm, coconut, peanut, sunflower, soybean [95], [97], [99]–[104]. However, developing countries like India, edible oil for biodiesel production should not appreciate as these countries have to fulfil their food requirement first. For these countries, inedible oil should be the first preference for biodiesel production. The number of research has been already conducted in which biodiesel is prepared from inedible oils like jatropha, Karanja, mahua, neem, rubber, and tobacco [50], [105]–[108].

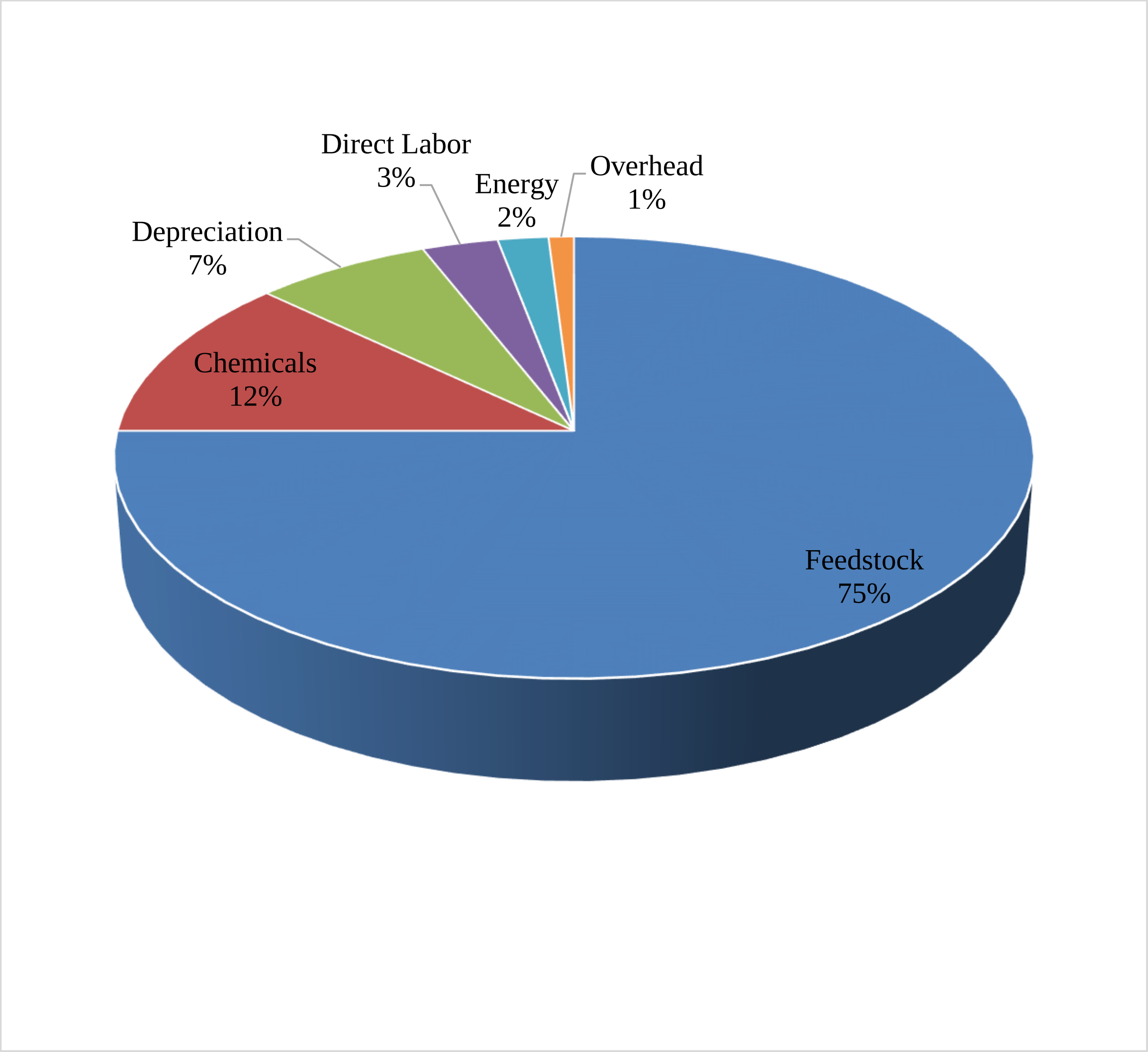


Figure 2.2: Head distribution of Biodiesel cost [95]

The performance of biodiesel prepared from edible and inedible oils are quite similar and comparable. Some of the researchers also prepared biodiesel from waste cooking oils and animal fats which also perform well on diesel engines [84], [109]–[111]. The number of researchers produces biodiesel from other sources as well like algae, microalgae, fungi, etc. These feedstocks are also renewable in nature and performing well [95], [112], [113].

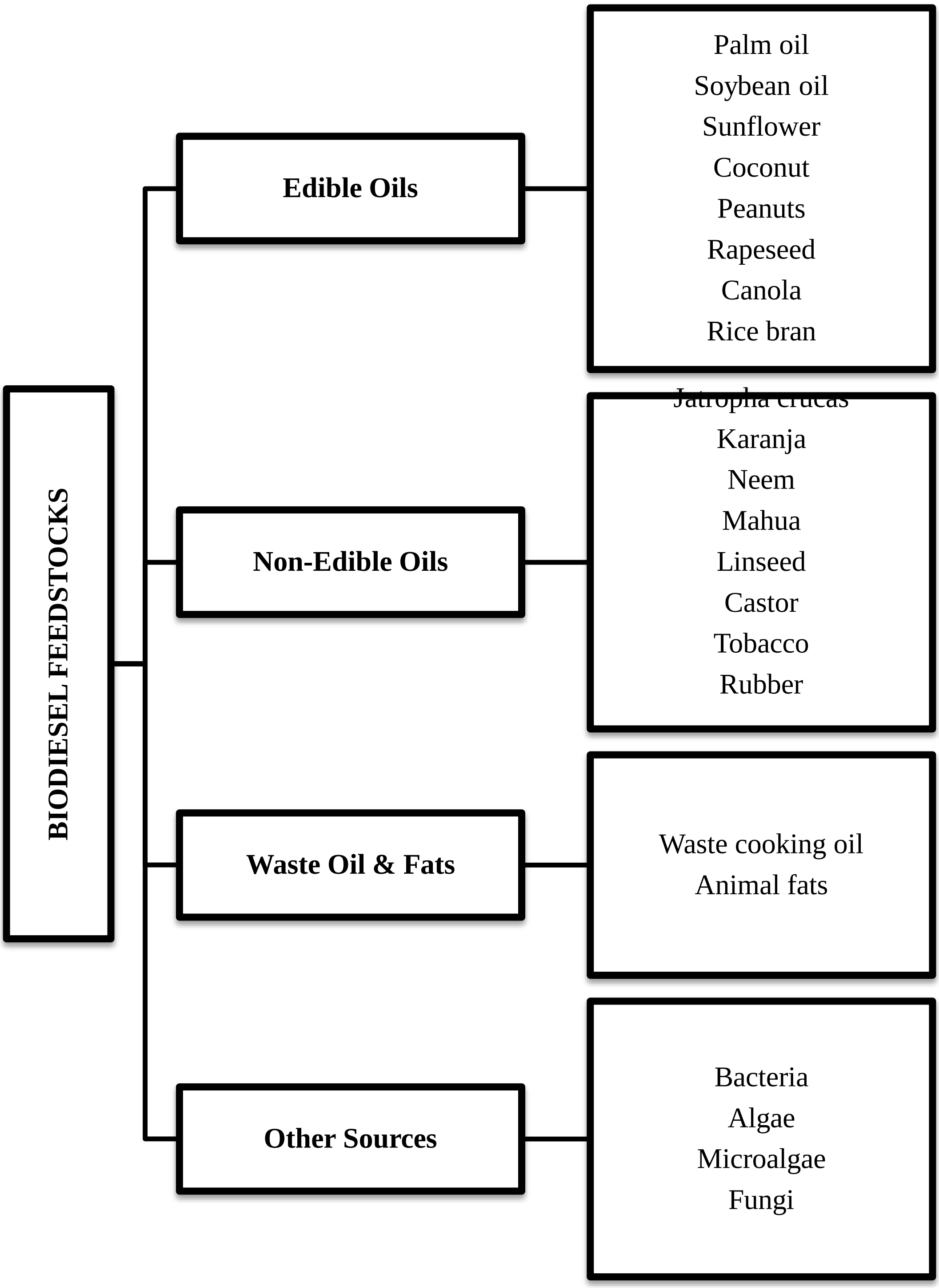


Figure 2.3: Classification tree of feedstock [48], [95], [114].

In India feedstocks used as fuel are inedible oil, waste cooking oil, and animal fat. The inedible oil contributes more than 50% and continuously increasing due to government policies and awareness among industries and consumers. The second place is secured by waste cooking oil. Some edible feedstocks are also used due to cheaper prices and availability. However, their contribution is very less as compare to inedible and waste cooking oil. These feedstocks are mainly used for the research point of view and to improve the overall properties of other biodiesel. The biodiesel in India also prepared from animal fats which include fish oil, beef fat, etc. The contribution is very less and not increase at an impressive rate. The biodiesel production from different feedstocks in million liters per year from 2010 to 2019 is shown in figure 2.4.

The frequently utilised feedstocks to produce biodiesel in India are jatropha (jatropha curcas), mahua, karanja, rubber seed, tobacco, canola, kusum, and neem in inedible oil. Some edible oil is nay utilised to produce biodiesel due to availability, price, production, and geographical regions. The main feedstocks in edible oil are palm oil and coconut oil. Some other feedstocks are also used for biodiesel production. These feedstocks are waste cooking oil, animal fats, and algae oil. However, the contribution of algae oil is negligible as compared to other feedstocks.

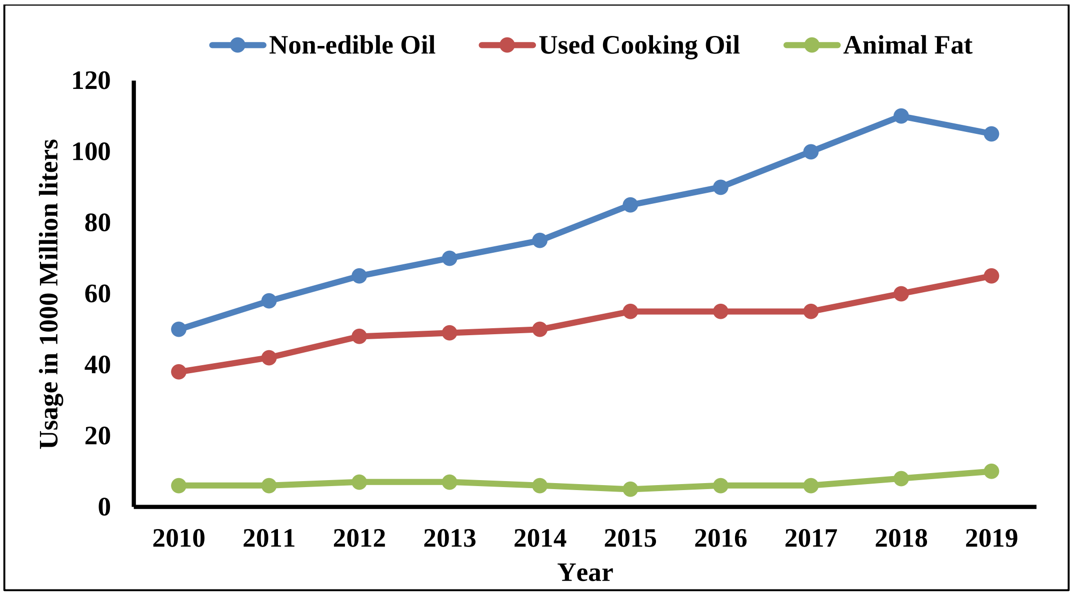


Figure 2.4: Usage of various feedstock as fuel from 2010 to 2019 [115].

2.4.1. Jatropha curcas

Jatropha curcas gaining popularity to produce biodiesel due to its non-edibility. The jatropha curcas belongs to the Euphorbiaceae family [116]. It is documented that, the jatropha curcas is originated from Africa. In the starting, it was cultivated in four countries of Africa: Cameroon, Ghana, Nigeria, and South Africa[117]. Jatropha curcas used for medical purposes in the starting after noticing its growth it is used as biodiesel feedstock. From Africa only it spread all over the world. The jatropha curcas is toxic in nature therefore it is used for various purposes except feeding to animals and human beings. However, non-toxic spices of jatropha curcas were found in Mexico [118]. This non-toxic spices of jatropha are not cultivated at other places due to less productivity. The main advantage of the jatropha plant that it can be cultivated on poor or marginal land as well. The jatropha plants also resist the drought and bound the land during the flood as well. Jatropha plants do not require more moisture to grow [119].

The “National Bureau of Soil and Land Use Planning” (NBSS&LUP) work to identify regions in India which are suitable for jatropha plantation using agroecological regional approach [31]. During this study, the complete country is divided into three regions according to the condition of the soil. The highly suitable region in which the jatropha can grow effectively and give better production. The moderately suitable region in which the chances of growing jatropha and production of fruits are quite high. The coastal area is moderately suitable for the growth of jatropha curcas. In the poor region, the chances of growth of jatropha are not so good. But it was found that jatropha grows in those regions as well. The representation of all these regions on the geometrical map of India is shown in figure 2.5.

Jatropha curcas is a short height (3-4 meter), soft wooded, evergreen tree spices that are growing in India at a very fast rate. The jatropha curcas plants produce fruits two times in a year and the first yield comes after two years of plantation. Some areas the first fruits come less than two years of age. The average life cycle of jatropha curcas plant is short than other normal plants it is around 30-40 years [118]. The yield in the jatropha plant comes two times a year after that also it comes under the category of moderate yield plant category. The production of jatropha oil is around 3 tonne per hectare which can produce 2.5 tonnes of biodiesel [118]. The yield of jatropha curcas is dependent upon the fertility of the land, moisture content, weather, and fertilizers used. The jatropha curcas is a very important and useful plant. The various parts of jatropha plants like seeds, leaf, flower, and stem are used for several purposes which are shown in figure 2.6.

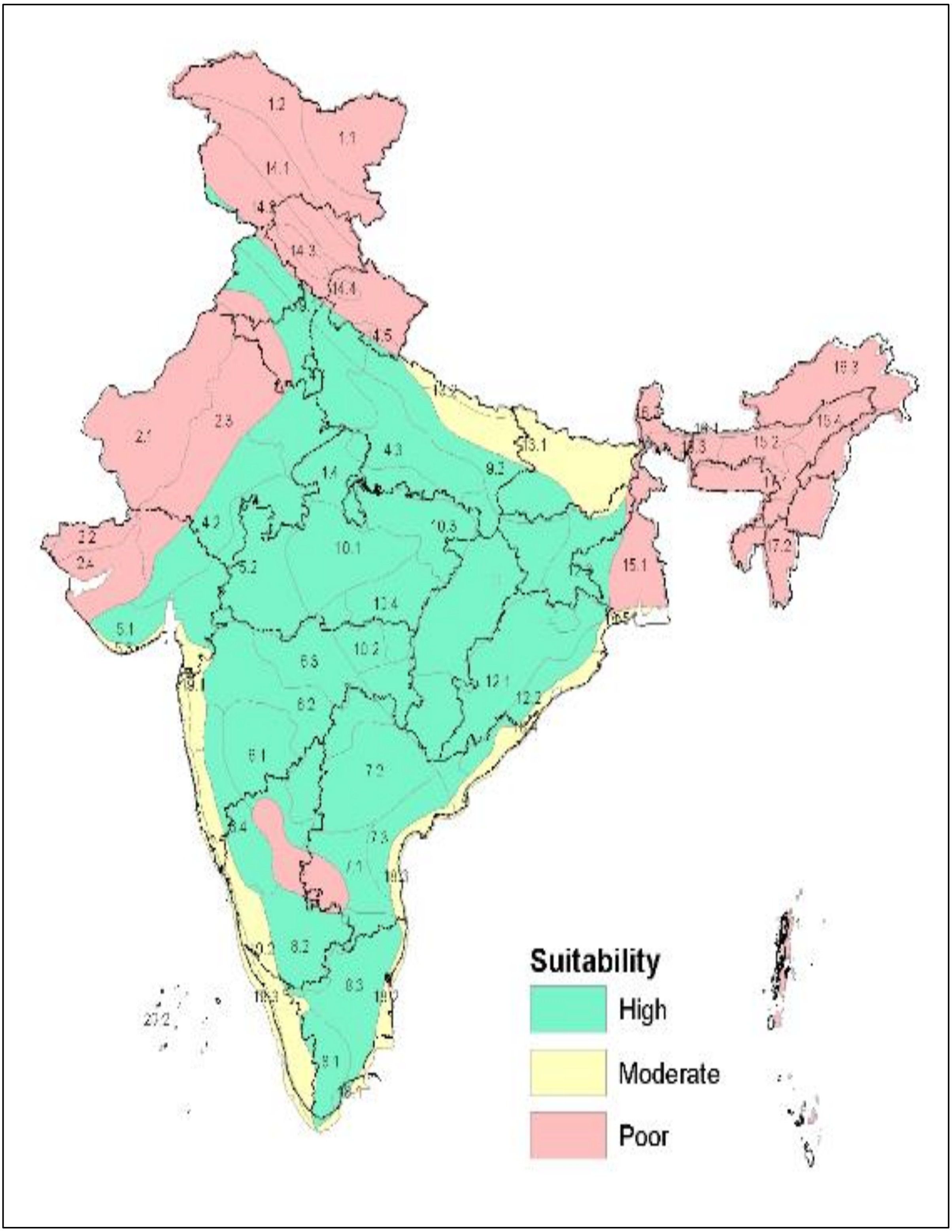


Figure 2.5: Stability map for jatropha curcas cultivation [31].

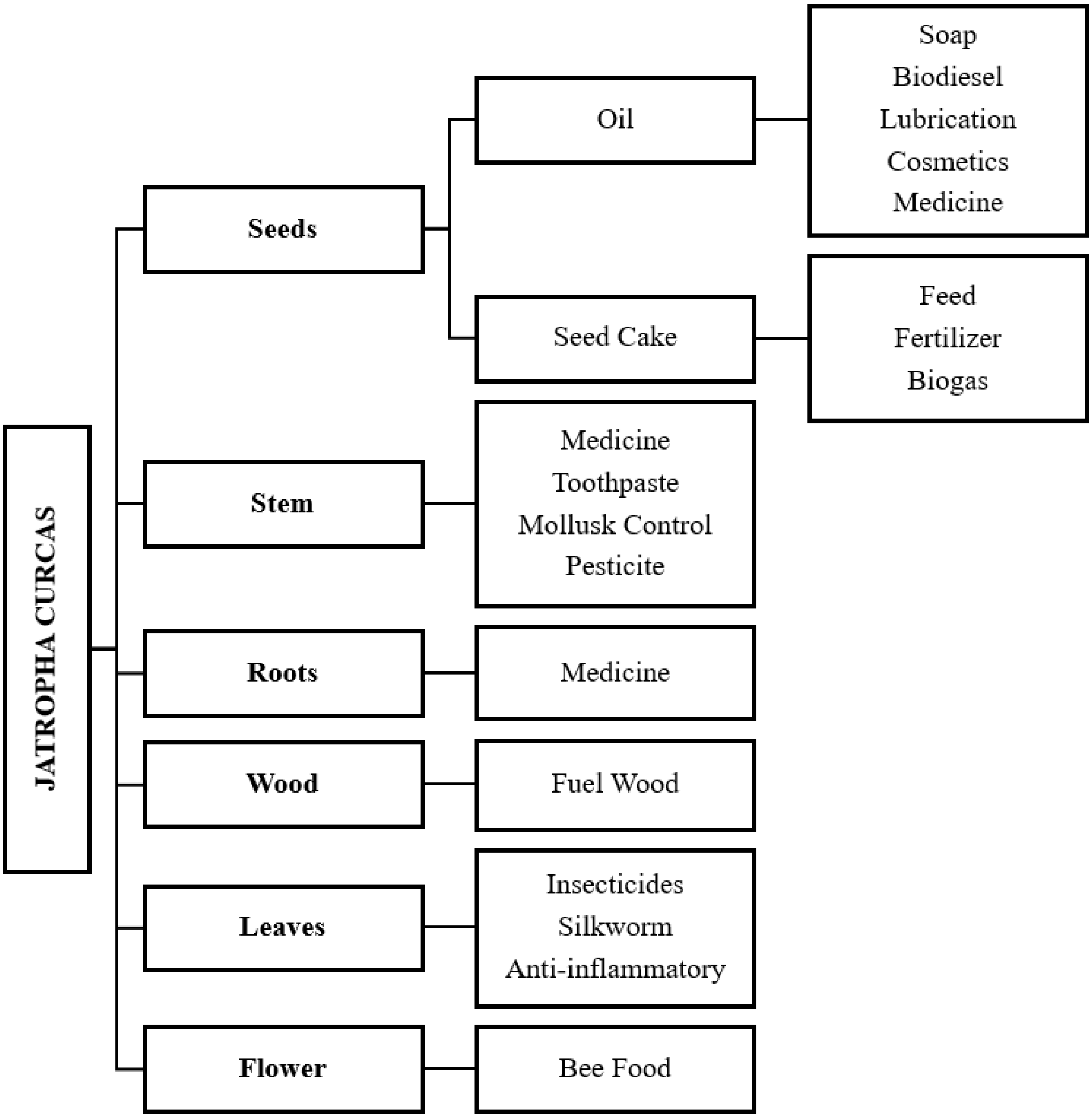
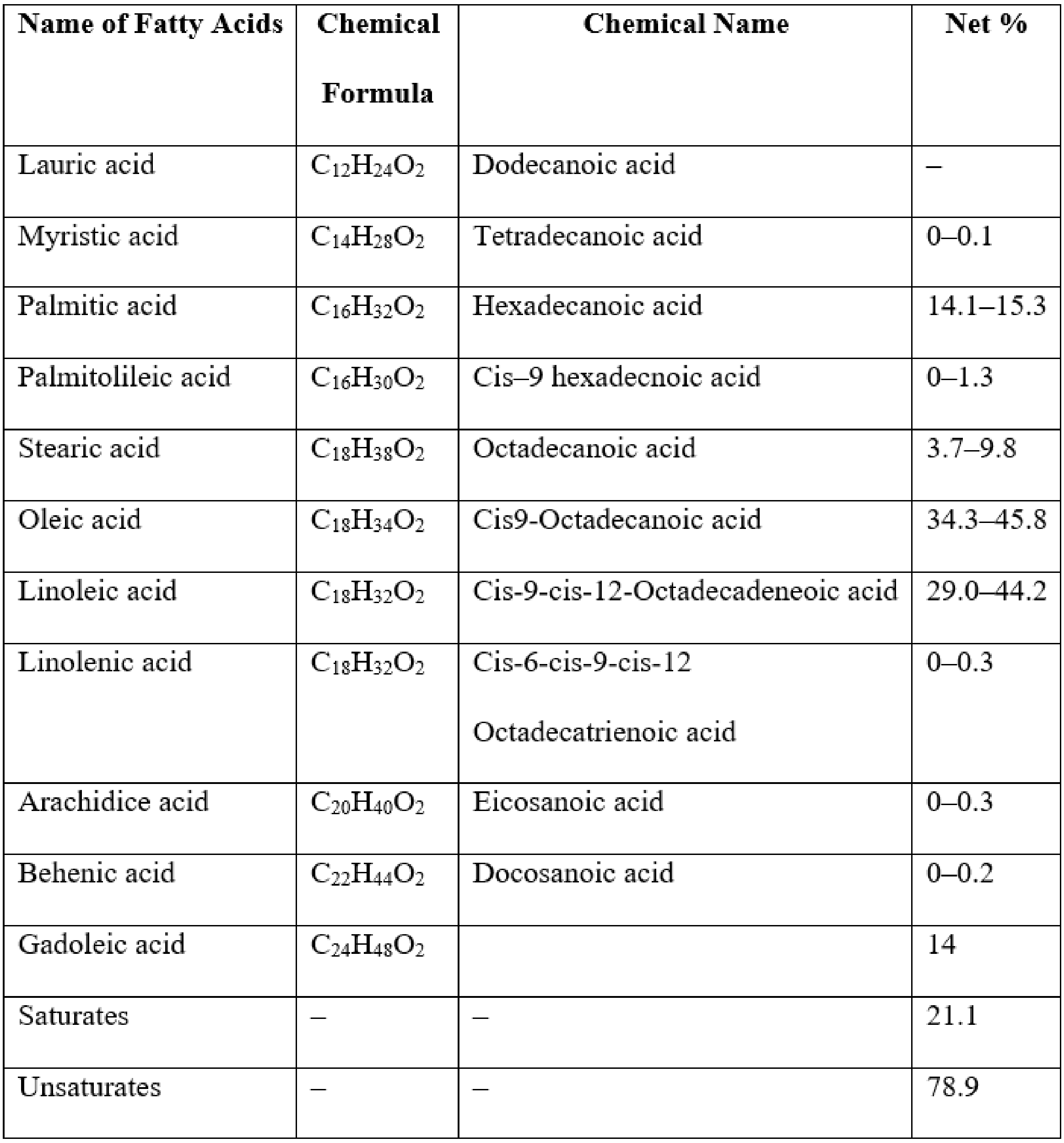


Figure 2.6: Use of different part of jatropha curcas [120], [121].

The oil content of jatropha seed is nearly 40% of its weight. However, the oil content varies spices to spices of jatropha curcas. The oil content also varies with the geographical condition, weather, and moisture content. The maximum oil content in jatropha seed is 47% of its weight [122]. The shell of jatropha seed contains 40% of its total weight and it is full of fibre only [123]. The complete oil is contained by the kernel of the seed and this value is around

40-60% of its total weight [118], [123]. The yield of the oil from the seed also depend upon the method and technology used for oil extraction [122], [124]. The jatropha oil (JO) contains the number of fatty acids which contain around 21.1% saturated fats and 78.9% of unsaturated fats. The composition of JO is shown in table 2.2.

Table 2.2: The composition of JO[124].



Name of Fatty Acids	Chemical Formula	Chemical Name	Net %
Lauric acid	$C_{12}H_{24}O_2$	Dodecanoic acid	–
Myristic acid	$C_{14}H_{28}O_2$	Tetradecanoic acid	0–0.1
Palmitic acid	$C_{16}H_{32}O_2$	Hexadecanoic acid	14.1–15.3
Palmitolileic acid	$C_{16}H_{30}O_2$	Cis–9 hexadecnoic acid	0–1.3
Stearic acid	$C_{18}H_{38}O_2$	Octadecanoic acid	3.7–9.8
Oleic acid	$C_{18}H_{34}O_2$	Cis9-Octadecanoic acid	34.3–45.8
Linoleic acid	$C_{18}H_{32}O_2$	Cis-9-cis-12-Octadecadeneoic acid	29.0–44.2
Linolenic acid	$C_{18}H_{32}O_2$	Cis-6-cis-9-cis-12 Octadecatrienoic acid	0–0.3
Arachidice acid	$C_{20}H_{40}O_2$	Eicosanoic acid	0–0.3
Behenic acid	$C_{22}H_{44}O_2$	Docosanoic acid	0–0.2
Gadoleic acid	$C_{24}H_{48}O_2$		14
Saturates	–	–	21.1
Unsaturates	–	–	78.9

2.4.2. Madhuca indica (Mahua)

Madhuca indica is spices of inedible oil famously known as mahua. The other famous names of madhuca indica are the Indian butter tree in English and mahua, mohwa, mauwa in Hindi [125]. Madhuca indica is Indian origin spices found all around the country. It is found in countries like Pakistan, Bangladesh, Sri Lanka, and Malaysia. Madhuca indica is frost resistance species and grows at an altitude of 1200 to 1800 in dry tropical and subtropical forests [126], [127]. Madhuca indica comes from Sapotaceae family [98], [125], [128]. The madhuca indica oil is used as a traditional medical purpose from long back [125]. The madhuca indica plant is shown in figure 2.7.

Figure 2.7: Madhuca indica (Mahua) plant and seeds

The oil is used for the number of diseases like Piles, Hemorrhoids, Emetics, Skin Disease, Rheumatism, Headache, etc. The other part of the plants like flowers, fruit, leaf, seeds is also used for traditional medicine purposes. 15-20% of oil extracted from madhuca indica seeds are used for medicinal purpose only. The indigenous production of madhuca indica oil India is approximately 60 million tons per year [127]. The length of the madhuca indica trees is approximately 12 to 20 meter and diameter is in the range of 80 centimetres [129].

The tree of madhuca indica starts giving fruits at the age of 10 years and continuously gives up to the age of 60 years. The fruits on the tree come one time in a calendar year and approximately 5 to 200 kg of seed is collected from one tree. However, the Sundry seed value comes around 1.6 to 20kg per tree. The fruits of madhuca indica are of orange brown in colour and each fruit contains 4 shining seed in it [125]. The oil content in the seed is nearly 40% of the weight of the seed. Similar to jatropha curcas, the oil content in the kernel is going up to 70% [125], [127]. The most of madhuca indica tree found in tribal areas which makes it a good source of alternative fuels for them [127]. The free fatty acid content of mahua oil is around 21% which is very high concerning biodiesel production [130]. With this high FFA mahua oil also cannot use in diesel engines as fuel. So the biodiesel of mahua oil can produce through two stages transesterification process and used as a blend with diesel in diesel engines [130].

2.4.3. Nicotiana tabacum (tobacco)

Nicotiana tabacum famously known as cultivated tobacco is an annually growing herbaceous plant [131]. Tobacco belongs to the Solanaceae family[50]. Tobacco is cultivated all over the world these days. However, it was originated from South and North America from where it introduced to the European countries in the 16th century. Presently, India secures second place in tobacco production and fifth place in exports of tobacco and its products worldwide [132].

The tobacco plant grows in the greenhouse effect and the effective growing temperature required is 25°C. The tobacco plants required 16 hours of sun/ artificial light for efficient growth [133]. Except its tobacco plant does not require any specific condition to grow. The height of the tobacco plant generally lies in the range of 1 to 2 meters [131]. The tobacco plant with flowers and fruits is shown in figure 2.8. As discussed earlier the tobacco is planted throughout the world due to a continuous increase in demand. The tobacco leaves are used for smoking and extraction of nicotine. The tobacco is also used in the number of traditional medicine all around the world. The leaves are applied externally as medicine for the number of diseases like painful piles, rheumatic swelling, strings, and skin diseases [131].

Figure 2.8: Tobacco plant and seeds

The oil is squirm from tobacco dry fruits & leaves. This tobacco oil (TO) is used in the number of medical purposes and various drugs are prepared from tobacco oil. The oil content in the tobacco seeds is in the range of 35-49% of its weight. Similar to other plants the oil contents depend upon weather conditions, soil fertility, and geographical location of the land. The fatty acid composition in tobacco oil lies in the range of 69.5 to 75.6% which mainly contains linoleic acid [50]. The properties of tobacco oil are quite impressive which attract researchers to use it into diesel engine. However, tobacco oil cannot use directly as fuel in a diesel engine as the FFA content of TO is higher than 17% which is too high to create problems in the engine [134]. Similar to mahua oil the biodiesel of tobacco oil is also prepared through two stages transesterification process.

2.4.4. Pongamia pinnata (Karanja)

Pongamia pinnata famously known as Karanja in India belongs to the Leguminosae family [50]. It is an evergreen plant generally found in India and its subcontinents [50], [135]. The plants belong to medium size and the height remains in the range of 15 to 25 meters [50]. The karanja plant with fruits is shown in figure 2.9. The plant is drought resistance, fast growing and mostly found in tribal and rural areas [136]. The plant and its products cannot use for feeding to the animals but the oil of karanja and its leaves are used for traditional medicinal purposes. The products of karanja are used to cure various diseases like wounds, piles, and the number of skin diseases [137]. It was found that pongamia pinnata is originated from India and its subcontinent and afterward it spread though out the world. Presently, pongamia pinnata is found worldwide but the main countries are: India, China, Australia, New Zealand and United State of America [138]. The plant can grow on land but the growth is better at an altitude of 1200 meters with rainfall in the range of 500 to 2500 millimeters [139]. The flower comes on the plant after the age of 4 to 5 years and the maturity will take the time of 7 to 8 years [50]. One single tree can produce seeds in the range of 9 to 90 kg and yield comes every year at the fixed time [48]. It was estimated that 900 to 9000 kg of seeds can be produced in one hector of plantation assuming 100 plants were planted [48], [135].

Figure 2.9: Karanja plant and seeds

Each dry seed of karanja carries a weight of 2 gram [139]. The oil content in the seed varies in the range of 30 to 40% of its weight. As karanja oil (KO) is inedible oil it cannot use for cooking purposes. This generates interest among the researchers to use karanja oil for biodiesel production. The number of work has been conducted in which researchers use biodiesel prepared from karanja oil in conventional diesel engines [140]–[142]. The karanja oil contains oleic acid and contributes nearly 45 to 71% of total weight followed by linoleic acid and stearic acids which contributes 11-18% and 2-9% respectively [50]. The FFA content of KO is also higher due to which it does not use in a diesel engine as fuel directly. The biodiesel of karanja oil is also prepared through two stages transesterification process.

2.4.5. Azadirachta indica (Neem)

Azadirachta indica is Indian and its subcontinent originated plant spices famously known as neem in Hindi. It is an evergreen plant belongs to the Meliaceae family [143]. Mostly the neem trees are found in India and its subcontinent like Pakistan, Bangladesh, China, etc. the neem plant can grow in any soil like dry, moisture, etc. this tree even can grow in deserts as well [48], [50]. The neem spread to other parts of the world from Asia and now it found everywhere but its presence is considerable in tropical regions of Australia [50]. The neem tree required 400 to 1200 mm of rainfall per year [48], [50]. Neem is a medium size plant that can attain an average length in the range of 12 to 18 meters [48]. The neem tree is shown in figure 2.10.

Figure 2.10: Neem plant and seeds

The maturity period of the neem tree is 15 years. However, maturity depends upon the care, fertilizer used, and weather conditions. The first fruit comes at the age of 6-8 years but it reaches its maximum productivity at the age of 15 years [48], [50]. The life span of the neem tree is in the range of 150 to 200 years and it gives fruit for its complete life span. The neem is used for traditional medicines from the very long back due to its good antioxidant and antimicrobial properties. In India, the neem is used for the number of purposes even for toothbrushes as well. The properties of neem plants and their oil are recognised by the world and now various countries like China, USA, Singapore, etc are using the products produced from the neem trees and its oil as herbal pesticides and for other healthcare products [143], [144]. Normally seed yield of one neem tree can varies from 30 to 50kg per years which again depend upon weather condition and fertilizer. The density of the neem tree is also very good compare to other medium-size trees. Nearly 400 tree plants can be planted in one hectare land. Further, if productivity is converted per hectare, neem trees can produce 2 to 5 tons of seed per hectare per year [143].

The oil content in seed lies between 20 to 30% of its weight. However, the oil content in the kernels is in the range of 40 - 50% [48], [50]. It shows that the shell of the neem seed does not contain any oil and the weight of shell is nearly 40% of seed weight. The neem oil is in brownish green colour [48]. The neem oil is found highly unsaturated and contains the number of fatty acid components [50]. The chief constituent of neem oil is oleic acid which is present in the range of 25 to 54% of total oil. The other components of the neem oil are linoleic acid and stearic acid which contribute 6 to 16 and 9 to 24 of total oil respectively [50]. The FFA content of the neem oil is rife than 10.

2.4.6. Schleichera oleosa (Kusum)

Schleichera oleosa is a member of the Sapindaceae family and famously known as Kusum in India [145]. It is distributed to all regions of Himalayas and from western Deccan to Sri Lanka [48]. The kusum is also found in China so also known as the Indo-China plant. From India kusum was introduced to Malaysia after that it was neutralised to Indonesia [48]. The average height of kusum tree varies in the range of 15 to 25 meters. Kusum tree can be grown in any type of soil and weather but the growth is effective at an altitude of 900 to 1200 meters [146]. The rainfall required for kusum tree is in the range of 750 to 2800 millimeters. The kusum tree is shown in figure 2.11.

Figure 2.11: Kusum plant and seeds

The kusum tree is used for the number of traditional medical purposes. The wood of the kusum tree is reddish in colour and very strong in nature [146]. The kusum tree wood is used to produce very good quality charcoal [48]. The kusum oil is used to cure etching, other skin diseases, hairdressing, and lightning [145]–[147]. The kernels of kusum seeds contain a cyanogenic compound which makes kusum oil toxic and inedible[148]. Kusum tree attracts and hosts the insects which produce high quality lacquer gum. Therefore the kusum tree is also known as Lac tree [146], [148]. The soap is also prepared from kusum oil but due to toxicity, the oil needs to pre-treat before saponification [146], [148]. The seeds of kusum tree come in the categories of higher oil contents. The oil content in kusum seeds varies from 59 to 72% of seed weight which highest among its category trees. The colour of kusum oil is yellowish green [147]. The composition of kusum oil is given in Table 2.3.

Table 2.3: Composition of KO

Name of Fatty Acids	Chemical Formula	Chemical Name	Net %
Lauric acid	$C_{12}H_{24}O_2$	Dodecanoic acid	1
Myristic acid	$C_{14}H_{28}O_2$	Tetradecanoic acid	2.1
Palmitic acid	$C_{16}H_{32}O_2$	Hexadecanoic acid	6.4
Palmitolileic acid	$C_{16}H_{30}O_2$	Cis–9 hexadecnoic acid	1.3
Stearic acid	$C_{18}H_{38}O_2$	Octadecanoic acid	1.5
Oleic acid	$C_{18}H_{34}O_2$	Cis9-Octadecanoic acid	43
Linoleic acid	$C_{18}H_{32}O_2$	Cis-9-cis-12-Octadecadeneoic acid	3.5
Arachidice acid	$C_{20}H_{40}O_2$	Eicosanoic acid	12.3
Eicosenoic acid	$C_{20}H_{38}O_2$	_	24

2.4.7. Hevea brasiliensis (Rubber)

Hevea brasiliensis belongs to Euphorbiaceae family[2], [48], [50], [149]. The literature suggested that the origin of this tree is from South America [2]. However, some studies suggest that hevea brasiliensis was originated from Brazil [48], [50], [149]. It was introduced to Southeast Asia as an industrial crop [2], [150]. The hevea brasiliensis tree is famously known as the rubber tree and used a number of purposes. The rubber tree is a rapidly growing plant. Further, it grows with a much faster rate at an altitude of 200 meters and a temperature of 27°C [2], [150]. The average height of the rubber tree goes up to 34 meters and comes in the category of the evergreen plant [2], [48]. The rubber tree is shown in figure 2.12.

Figure 2.12: Rubber plant and seeds

The latex of purity 60% is obtained from the rubber tree which used for various purposes [151]. The oil can extract from the rubber seeds which contributes 40 to 60% of the weight of seed [2], [50]. The rubber seed oil is brownish in colour [152]. Generally, the weight of a dry seed of rubber tree is 2 - 4 gram [2], [48], [152]. One normal rubber tree gives a yield of 5 kg of seeds and in one hectare nearly 150 kg of rubber tree seeds can be produced. The rubber tree seeds production in India goes up to 30000 tons per year from which the rubber oil of approximately 5000 tons is produced in one calendar year [152]. More than 70% of rubber collected from the rubber tree is used for tyre manufacturing [153]. However, the use of natural rubber and rubber oil is reduced due to synthesis rubber. Therefore, biodiesel can be produced from rubber tree oil [152].

The FFA content of rubber oil is around 17% which is much higher than normally required. The higher FFA content is due to unsaturated and saturated acid present in rubber oil.

The rubber oil contains 80.5% of unsaturated fatty acids which are: linoleic acid (39.6%), linolenic acid (16.3%), and oleic acid (24.6%). Apart from it rubber oil also contains 18.9% of saturated acid which is contributed by stearic acid (8.7%) and palmitic acid (10.2%) [2], [50]. However after high FFA content also the biodiesel yield is more than 98% which very high among all high FFA feedstocks [2].

2.4.8. Ricinus Communis (Castor)

The origin of ricinus communis plant was reported from Brazil. From where it was introduced to India and Chine nearly 1400 years back [154]. In India, the ricinus communis plant is known as castor beans. Due to very slow growth, the castor tree is also used as an ornamental plant all over the world [155]. From the study, it was found that the castor tree attains a height of 45cm only after 5 to 6 months of plantation [156]. The normal height of the fully matured castor tree is 1-2 meters however in some special cases it can attain a height of 3 to 5 meters [157]. The castor tree is shown in figure 2.13. The castor tree developed throughout the tropical region of Eastern Africa, China, and India [155]. According to research and data, 90% of castor oil is developed in China and Brazil only [154].

The various parts of the caster tree like a leaf, seed oil, and root are used as traditional medicine for the number of diseases and treatments. The castor oil is used for treatment and precaution of piles. The three parts are also used for the treatment of the liver disorder, inflammation treatments, etc. [155]. The seed of the castor tree is a dark brown colour. The normal yield of castor seed is around 650 tons per hectare. However, in the Philippines the

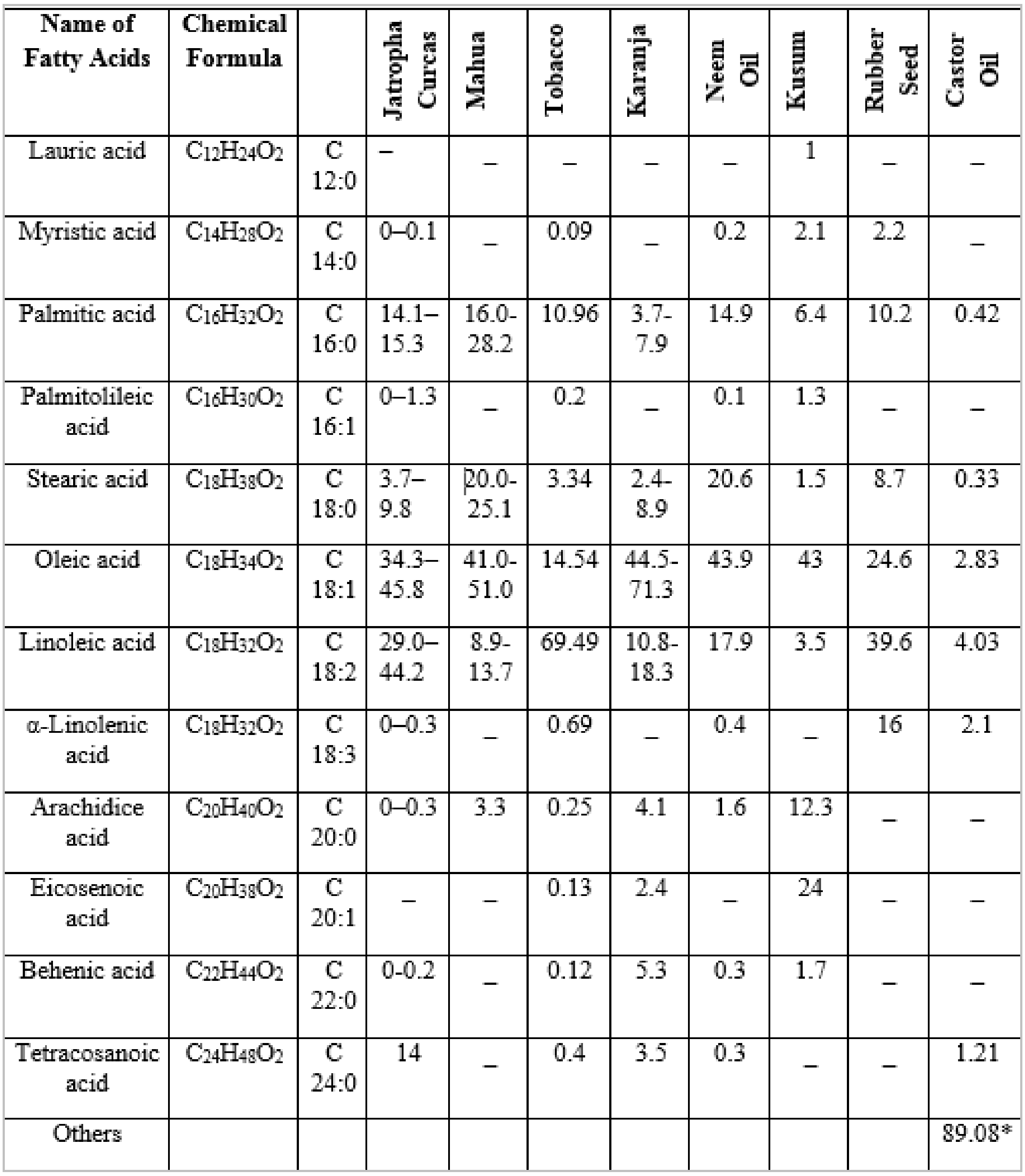
Figure 2.13: Castor plant and seeds

the yield goes up to maximum value i.e. 3636 tons per hectare on the other side the lowest yield of castor seed was noticed in Burundi which is 160 tons per hectare [157]. The weight of the kernel is 25% of the weight of seed. The oil percentage in the castor seed is in range of 35 to 45% which means the shell of the castor seed also contains oil. The castor seed is very light in weight, the weight of 1000 seed is around 650 grams. During cold press oil extraction, approximately 1 tonne of castor seed cake is produced for each0.5 to 0.6 tonne of castor seed oil. The cake is rich in nutrition and fibres so it is a good product and used as fertilizer and soil enhancer [158]. The castor oil contains 90% of ricinoleic acid which contains very unique properties like lower melting point (5C), higher molecular weight, and higher and most stable viscosity [119].

2.4.9. Fatty acid profile

All edible, non-edible, animal fats, algae oil are made up of various fatty acids in the different proportions which include saturated and unsaturated fatty acids. The composition of all inedible feedstocks discussed in this chapter is given in table 2.4.

Table 2.4: Fatty acid profile of all discussed inedible feedstocks [48], [159].



Name of Fatty Acids	Chemical Formula		Jatropha Curcas	Mahua	Tobacco	Karanja	Neem Oil	Kusum	Rubber Seed	Castor Oil
Lauric acid	$C_{12}H_{24}O_2$	C 12:0	–	_	_	_	_	1	_	_
Myristic acid	$C_{14}H_{28}O_2$	C 14:0	0–0.1	_	0.09	_	0.2	2.1	2.2	_
Palmitic acid	$C_{16}H_{32}O_2$	C 16:0	14.1–15.3	16.0-28.2	10.96	3.7-7.9	14.9	6.4	10.2	0.42
Palmitolileic acid	$C_{16}H_{30}O_2$	C 16:1	0–1.3	_	0.2	_	0.1	1.3	_	_
Stearic acid	$C_{18}H_{38}O_2$	C 18:0	3.7–9.8	20.0-25.1	3.34	2.4-8.9	20.6	1.5	8.7	0.33
Oleic acid	$C_{18}H_{34}O_2$	C 18:1	34.3–45.8	41.0-51.0	14.54	44.5-71.3	43.9	43	24.6	2.83
Linoleic acid	$C_{18}H_{32}O_2$	C 18:2	29.0–44.2	8.9-13.7	69.49	10.8-18.3	17.9	3.5	39.6	4.03
α-Linolenic acid	$C_{18}H_{32}O_2$	C 18:3	0–0.3	_	0.69	_	0.4	_	16	2.1
Arachidice acid	$C_{20}H_{40}O_2$	C 20:0	0–0.3	3.3	0.25	4.1	1.6	12.3	_	_
Eicosenoic acid	$C_{20}H_{38}O_2$	C 20:1	_	_	0.13	2.4	_	24	_	_
Behenic acid	$C_{22}H_{44}O_2$	C 22:0	0-0.2	_	0.12	5.3	0.3	1.7	_	_
Tetracosanoic acid	$C_{24}H_{48}O_2$	C 24:0	14	_	0.4	3.5	0.3	_	_	1.21
Others										89.08*

*Ricinoleic acid ($C_{18}H_{34}O_3$)

Advantages of inedible feedstocks:

The researchers are showing more interest in producing biodiesel from inedible oil due to their various benefits and government policies. The inedible feedstocks carry a number of benefits while using for biodiesel production. Some of these benefits and advantages are as follows:

- The utilisation of inedible oil help to secure the food scarcity of the country.
- The plants of inedible oil can be planted at wasteland or poor land where the edible crops are not possible to cultivate.
- The various varieties of inedible plants are available that nurture in a very small rainfall of 20cm. Also, a number of species of inedible plants are available which can grow easily at very high rainfall as well.
- The inedible feedstock trees also are planted on non-agricultural areas like fences of field and path provided for the field.
- Almost all the inedible species are drought resistance and improve the water level of the earth.
- As no specific space is required to plant these tree so they do not compete with existing resources available for agriculture.
- The number of different plants can be planted at the same place according to maturity time so that continuous fruit production takes place throughout the year.
- The wood collected from this tree can be used as an energy source for various purposes.
- All the inedible plants are renewable and carrying better properties like high heating value, low sulphur content, better density, and kinematic viscosity than edible oil plants.
- The plant absorbs CO_2 present in the atmosphere to prepare their food. So it was found that one hectare of green tree land fixes approximately 10 tons of CO_2 in one year [160]

Limitations of inedible feedstocks

The utilisation of biodiesel as an alternative fuel to run prime mover is one of the biggest achievements to increase self-sustainability for energy sources. As discussed earlier due to a number of advantages of inedible feedstocks over edible feedstocks, the inedible feedstocks gaining the interest of researchers, government, and industrialists. However, utilisation of inedible feedstock comes with some disadvantages as well. Some of the disadvantages are as follows:

- The plantation of inedible plants required time and revenue. The growth of the plants is also slower than edible plants.
- The efficient growth of these plants required advanced technology, fertiliser, and care after plantation.
- These plants are inedible and some of them are poisonous in nature. So they become a threat to an animal's life.
- Presently, the cost of most of the inedible feedstocks is higher compared to edible feedstocks because of limited accessibility & their utilisation in traditional medicines.

2.5. Methods of Biodiesel Production

The use of vegetable oils as fuel for transportation prime mover comes with the solution of the two biggest problems for any developing country i.e. self-sustainability for energy sources and fulfillment of continuously increasing demand for energy. However, the main targeted concern is self-sustainability only because most developing countries do not have enough energy reservoirs they have to depend upon the import of energy sources. The use of vegetables and waste oil as an energy source for engines seems a great step in this direction. However, the viscosity of straight vegetable oils is the biggest concern in this direction. The viscosity of most of the vegetable oils is very high compare to petroleum fuels, that's why the straight vegetable oils cannot use directly in the unmodified engine as they can cause choking of the fuel pump, fuel supply line, and fuel injectors. Also, they have a poor vaporising property which creates a problem during combustion. The use of straight vegetable oil in the engine also forms gum inside the cylinder which causes sticking between piston and cylinder and blocking of intake and exhaust valves. So to overcome these problems the viscosity of straight vegetable oil needs to decrease.

There is a number of methods that can be utilized to decrease density & kinematic viscosity of straight vegetable oil. Some of them are very effective and used by a number of researchers but some methods are time as well as energy consuming due to which they cannot able to fix their place for research. The name of some of the methods are given in figure 2.14 and they have explained afterward in the same section.

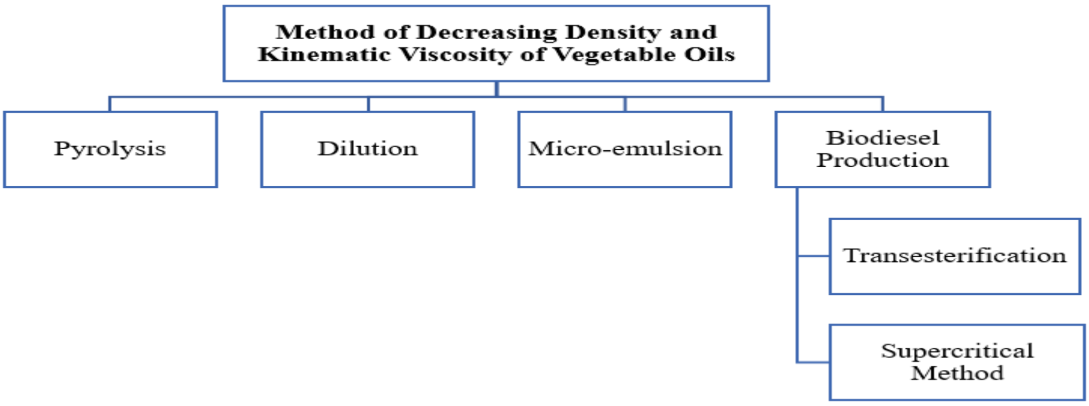


Figure 2.14: Methods of decreasing density and kinematic viscosity of vegetable oils [161].

2.5.1. Pyrolysis

The torrid thermal disintegration of lignocellulosic biomass in the presenceof partial presence of oxygen. The catalysts can also be used to enhance the rate of reaction. This lignocellulosic biomass can be anything waste cooking oil, animal fat, edible &inedible vegetable oil. Actually, pyrolysis derived from two Greek words i.e. ‘pyro’ which stands for fire and 'lysis' which stands for division in smaller parts [162]. This is assumed that this technology comes from the Middle East or Southern Europe where this technology is used to prepare charcoal 5500 years back [162]. Presently, this technology is used to prepare diesel like fuel from any vegetable oil, animal fat, and waste fat. This technology also used to convert biomass into different gaseous and liquid fuels. During this process, the oil, fat, or any biomass is heated above its boiling point where that convert into vapours and those vapours are condensed and different vapours of a different condensing point are collected according to requirement. As discussed in the earlier section that all oils & fats have different components and all these fatty acids have a different boiling point. So in this process, these fatty acids are condensed and collected into different containers.

The liquid prepared through the pyrolysis process has nearly similar properties as diesel fuel. The kinematic viscosity and density of paralyzed oil are less than the parent oil and seen lighter in colour. The other properties like heating value, pour point, flash point fire points of pyrolyzate is also better than straight vegetable oil and comparable with diesel fuel. However, the pyrolyzate oil has a lower cetane number than diesel fuel. But this will not the case of all feedstocks, some feedstocks have a higher cetane number than diesel. The decomposition temperature range of various biomass constituents is shown in figure 2.15.

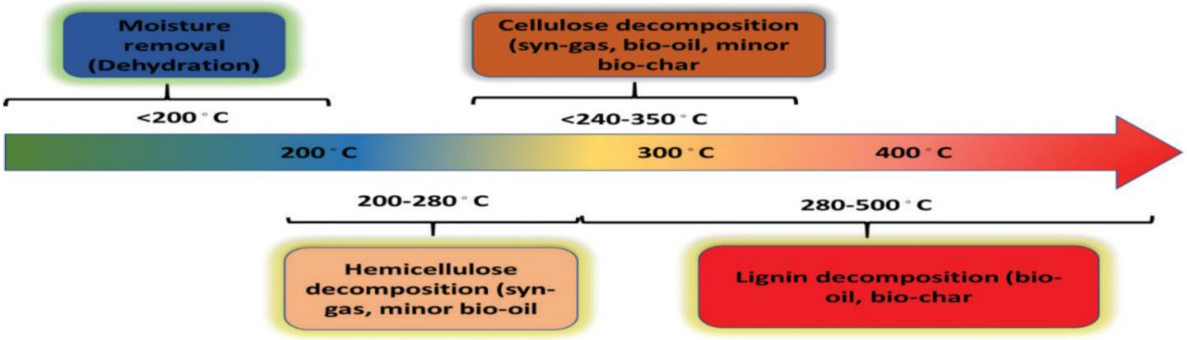


Figure 2.15: Biomass constituents, decomposition behaviour at various ranges of temperature [162].

The pyrolysis process has various advantages like it is a very simple and effective process to decrease the viscosity and kinematic viscosity of vegetable oils and waste fats. The waste product produced during pyrolysis is also very less nearly negligible and this process is also pollution free [163]. The pyrolysis process also not required any drying, filtering, and washing. However, the pyrolysis has various disadvantages as well like, pyrolysis takes place at a very high temperature so to achieve and maintain that temperature lot of energy is required [161]. The process also required expensive instruments and equipment. The quality of biodiesel produced through pyrolysis is also not up to the mark.

2.5.2. Dilution

Dilution is another method of reducing density and kinematic viscosity of straight vegetable oil. Similar to the pyrolysis method, this process need not required thermal cracking or catalyst. During dilution, the straight vegetable oil is directly mixed with low density and viscosity fuel in different proportions. The density and kinematic viscosity of the prepared mixture is less than the viscosity and density of parent oil. The mixture gets characteristics of both straight vegetable oil and diesel. Generally, 10 to 40% of straight vegetable oil is assorted with mineral diesel and prepared blends can be utilised in the compression ignition engine. Mixing of vegetable oil more than 40% by weight leads to an increase in the density & viscosity of prepared mixture that again may cause the problem in engines. The vegetable oil contains fewer sulphur contents and the free oxygen is also available in the vegetable oil which makes them a good fuel for higher load conditions. The blend of vegetable oil and other fuels has better combustion characteristics as related to mineral diesel and gasoline.

The dilution process is very simple among all other processes used to decrease the kinematic viscosity of the vegetable oil. The dilution process not required extra chemical and complex equipment and instruments. Therefore the dilution process is completely pollution free process. However, it carries some disadvantages as well. The density and viscosity of the prepared blend are higher than petroleum diesel fuel which might cause cocking of fuel spray nozzle and fuel supply line.

2.5.3. Micro-emulsion

The micro-emulsion is similar to the dilution process just difference in solvents used for mixing. In the micro-emulsion process, the waste fat or vegetable oil is mixed with a solvent like alcohol and surfactant. The alcohols can be basic alcohols like methanol, ethanol, or higher alcohols like butanol, octanol, pentanol, etc. The proportion of waste fat or vegetable oil and solvent is selected in such a way that it achieves the density similar to diesel fuel. In some cases, a little quantity of cetane improver or other property enhancer is added into the solution. The solution during micro-emulsion can be prepared with or without the presence of petroleum diesel in it. The micro-emulsion process does not require any large and advanced equipment similar to dilution. So this process is very simple, economical and pollution free. However, the problem like solubility, phase separation might occur with the prepared solution. The solubility and phase separation problem might vary with solvent and feedstocks.

2.5.4. Biodiesel production

The higher viscosity and density of waste fat and vegetable oil is the biggest challenge in projecting these as alternative fuels for internal combustion engines. However, the above discussed methods are used to decrease the density of waste fats and vegetable oil and use by a number of researchers. All the above discussed processes have their own limitation which leads to raise the question on their commercial use. The pyrolysis has time and energy consuming processes with a low yield of diesel-like fuel. However, the loss in the pyrolysis process is negligible which the biggest advantage of that process is. On the other hand, processes like dilution and micro-emulsion are very easy and economical as well but these contain some proportion of waste fats and straight vegetable oils. The presence of these fats and oils can form glue in the combustion chamber which can cause sticking between piston and valves. The presence of straight vegetable oils and waste fats can also cause cocking of fuel injector and fuel pipeline. Therefore, the new advanced process for decreasing the viscosity of waste fats and vegetable oil is found by researchers. The effective method of reducing the viscosity of SVO is known as biodiesel production. The biodiesel of waste fats and straight vegetable oil can be produced by two methods these are:

a. Transesterification
b. Supercritical method

2.5.4.1. Transesterification

Biodiesel is the methyl esters which can be prepared from any fatty acid. Transesterification is the most commonly preferred technique for biodiesel production. This technique gaining popularity due to its simplicity, higher yield, less time consuming, economical, and most important is the properties of fuel prepared through this method. In the transesterification process, the fatty acids react with alcohol with and without the presence of catalysts at a specific temperature. Generally, alcohols utilised during transesterification are lower carbon alcohols like methanol and ethanol. However, the biodiesel can also be produced with higher carbon alcohols like butanol, octanol even with decanol as well. In the transesterification process, one mole of straight vegetable oil or waste fat is reacted with three moles of alcohol in the presence of a catalyst and produces three moles of fatty ester and one mole of glycerol. The production of glycerol from triglycerides is a stepwise process. The triglycerides start reacting with alcohol and converted into diglycerides which further converted into monoglycerides and finally converted into glycerol. The density of glycerol is higher than the other product i.e. fatty esters produced during reaction so it can be easily separated from the fatty esters through gravity separation. The fatty acids are lighter in weight so it left in the separating funnel and this is famously known as biodiesel. The by-product of the reaction i.e. glycerol can be used in a number of cosmetic products. The chemical structure of triglycerides and other glycerides i.e. diglycerides and monoglycerides form during transesterification is shown in figure 2.16, 2.17, and 2.18 respectively.

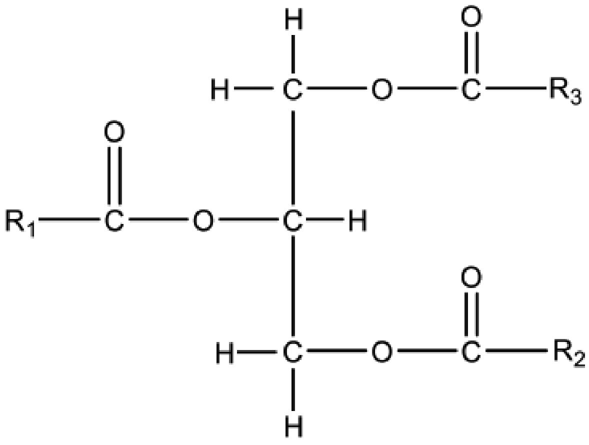


Figure 2.16: Triglyceride

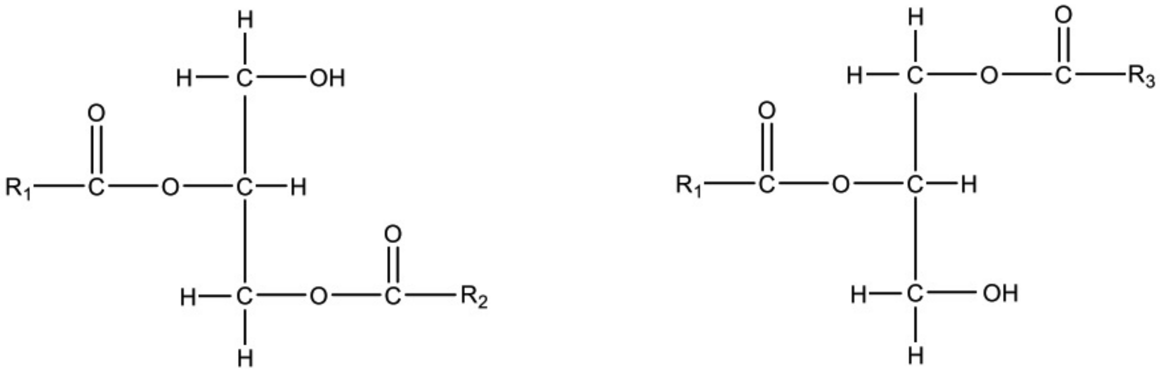


Figure 2.17: Di-glycerides

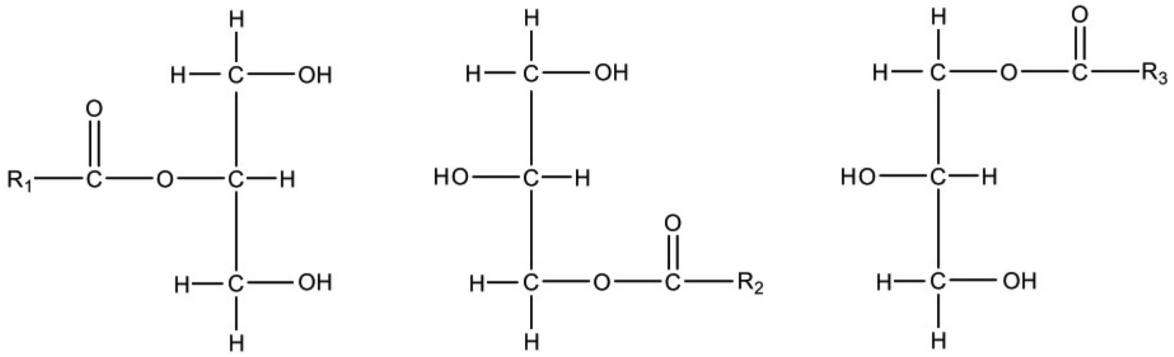


Figure 2.18: Mono-glyceride

As discussed earlier that the catalysts are used to enhance the rate of reaction. Mainly two types of catalysts are used for the transesterification process.

- Alkaline catalysts
- Acidic catalysts

The alkaline catalysts are commonly used for biodiesel production through the transesterification process. It was found that the use of alkaline catalysts enhances the reaction rate by 4000 times for the same yield on the same reaction temperature and the same molar ratio [164], [165]. This transesterification is also known as alkali- catalysed transesterification. The use of alkaline catalysts for biodiesel production enhances the yield and increases the purity index of biodiesel in a shorter period of time. The main alkaline catalysts used for biodiesel production are potassium hydroxides (KOH), sodium hydroxides (NaOH), potassium methoxides ($KOCH_3$), and sodium methoxides ($NaOCH_3$). The use of methoxides of sodium and potassium in the transesterification process leads to higher yield as compared to their hydroxides, but the cost of methoxides is much higher than hydroxides which increase the overall cost of the biodiesel. This results in higher utilisation of NaOH and KOH as alkaline catalysts for the transesterification process. Both KOH and NaOH give similar kinds of results when used for biodiesel production.

The transesterification process with homogeneous alkali-catalysts is shown in figure 2.19. During this process a homogeneous mixture of alkaline catalysts and alcohol is prepared in this process the alcohol reacts with catalysts and form alkoxide ion. This mixture is poured in the fatty acid where this alkoxide ion reacts with carbon atoms present in the fatty acids. This reaction forms tetrahedral intermediate compounds. This is the first step of transesterification chemical reaction. After that, this form intermediate compound, the chemical structures of these chemical compounds are given below. At the end of the transesterification process, the glycerol and fatty esters are formed [166], [167]. However, the FFA content in straight vegetable oil or waste fats should be in the range of 0.5% to 3% for alkali-catalysed transesterification process. If the FFA substances are more than mentioned value the soap can be formed instead of biodiesel [168]. The drift chart of biodiesel production through alkali-catalysed transesterification process is exposed in figure 2.20.

Another way of performing the transesterification process is by using acid catalysts like ferric sulphate acid ($Fe_2O_{12}S_3$), hydrochloric acid (HCl), sulphuric acid (H_2SO_4), para toluene sulfonic acid ($CH_3C_6H_4SO_3H$), phosphoric acid (H_3PO_4) and Lewis acids ($ZnCl_2$). During the research, it was found that the acid catalysts are more endurable as compare to alkaline catalysts. Therefore, the acid catalysts are utilised during the esterification process through this technique FFA of oil is decrease if it is greater than the desired limit (i.e. 2%) in the alkali-catalysed transesterification. Once the free fatty acid contents come less than 2%, the alkali-catalysed transesterification is performed for biodiesel production. The acid catalysts transesterification is also time consuming. The time taken during acidic catalysed transesterification is in the range of 1to 3hours while on the other end the alkali-catalysed transesterification takes only 30 to 120 minutes to depend upon the feedstocks.

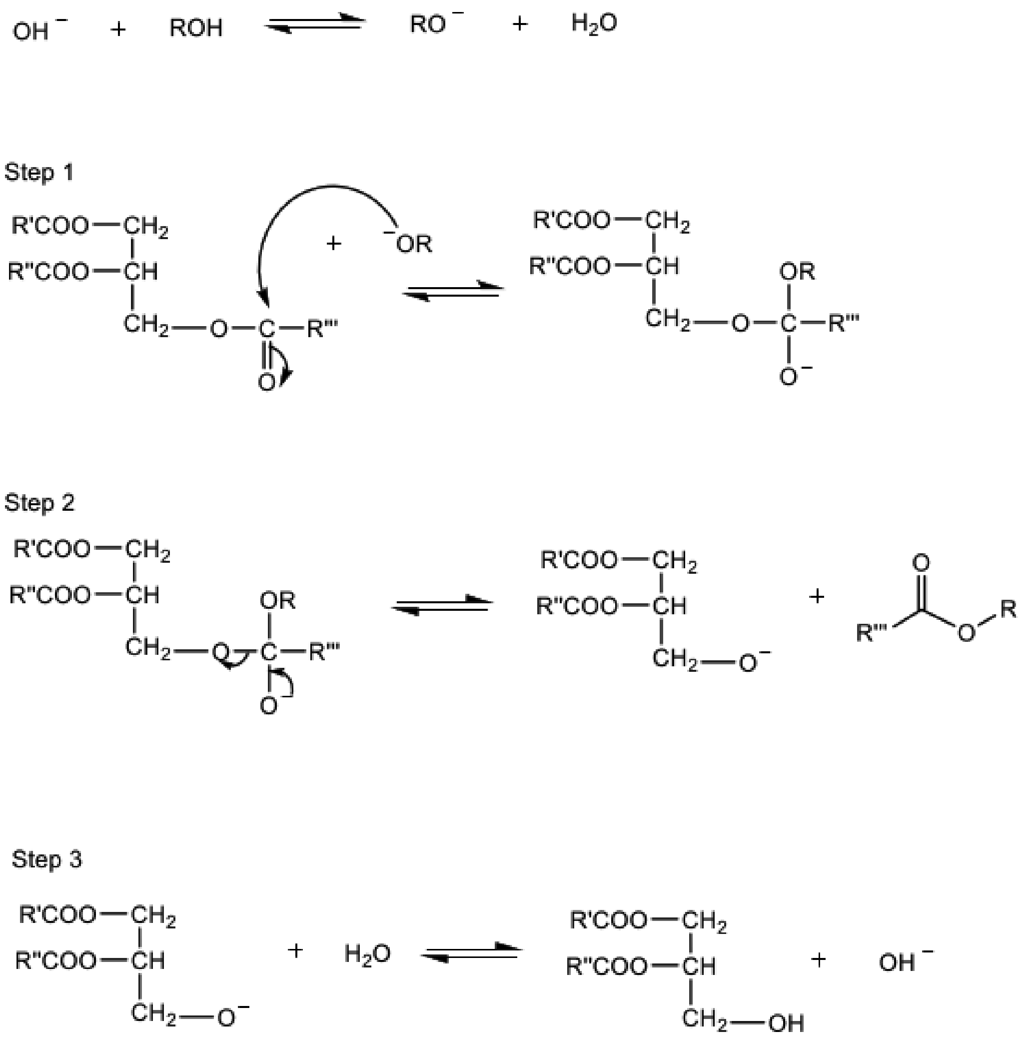


Figure 2.19: Alkali-catalysed transesterification reaction [169].

During the neutralising process, the salt is added therefore, the removal of that salt large amount of water is required. This process is also known as wet washing. The water used during wet washing cannot be utilised further for any other purpose. However, the acidic catalysed transesterification process has some advantages like high yield, low energy requirement, and low-cost reactants and catalysts. The yield of acidic catalysed transesterification process is 0.5% to 3% higher than alkali-catalysed transesterification. Although the acidic catalysed transesterification has a number of advantages, but it did not get its popularity due to the limitations like more time consuming, large water wastage, poor separation of products and poor catalysts solubility. To overcome these problems a new technique of biodiesel production is introduced which is known as supercritical esterification.

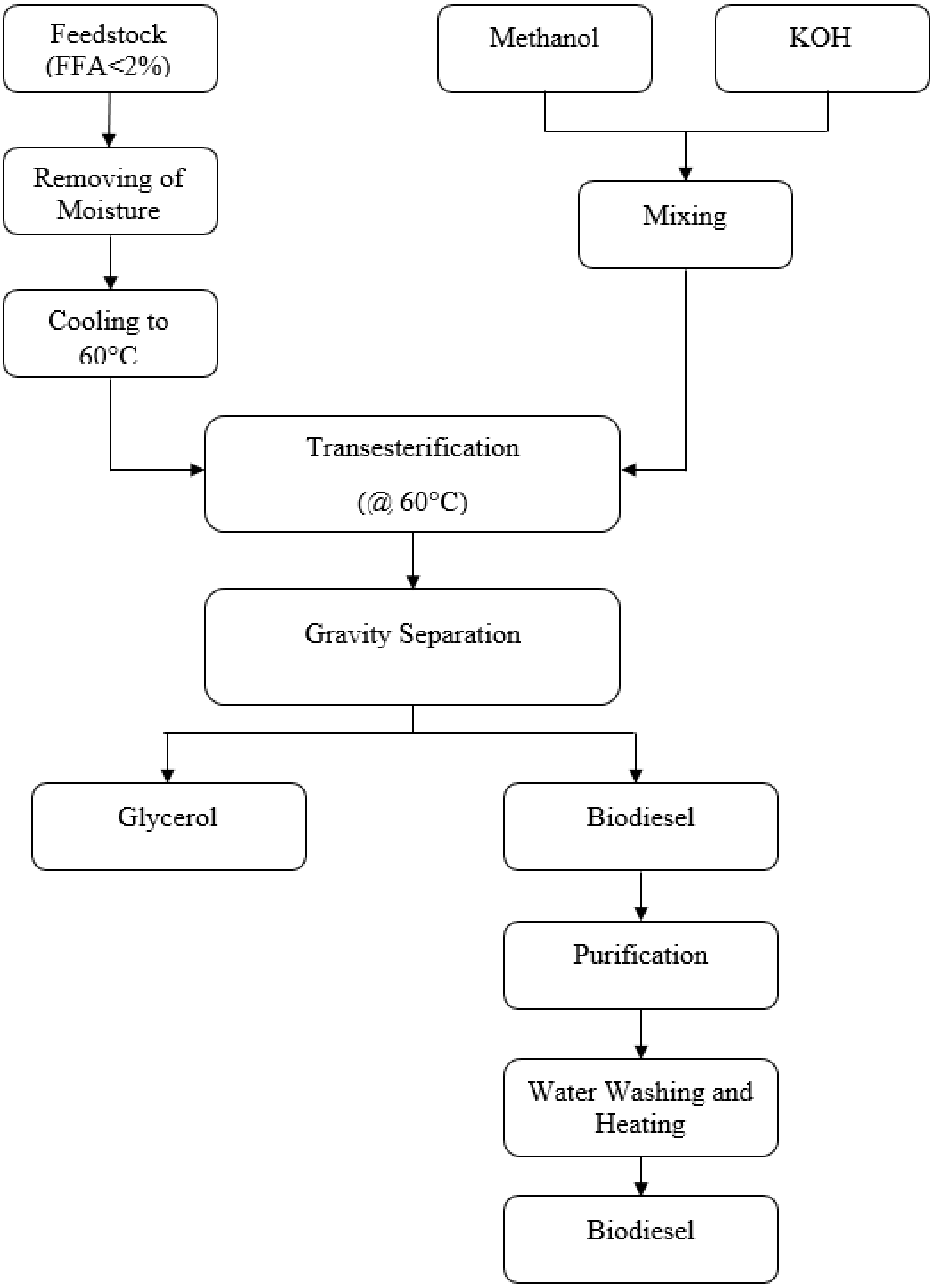


Figure 2.20: Flow chart of Alkali-catalysed transesterification

2.5.4.2. Supercritical method

The traditional transesterification processes (both alkali-catalysed and acidic catalysed transesterification) have some limitations like wastage of large quantity of water, time consuming, difficulty in handling high free fatty acid content feedstocks and difficulties in separation of fatty esters and glycerol. Apart from it, the traditional transesterification process required catalysts to increase reaction rate which changes the properties of the end product if not removed and the removal of catalysts is very difficult. To overcome all these problems that occur in the traditional transesterification process, Saka and Dadan, 2001 introduce a new and very fast method of producing biodiesel without using any catalyst through supercritical conditions [170]. In this new method, the triglycerides are reacted with supercritical alcohols without catalysts. The critical pressure and critical temperature of methanol are 8.1 MPa and 239.2°C respectively [171]. The supercritical method has various advantages over traditional transesterification process some of these are as follows:

- The biodiesel of higher FFA feedstock can also be prepared easily.
- During the supercritical transesterification process, the esterification and transesterification process occurs simultaneously for high FFA feedstocks.
- The reaction rate in the supercritical method is very fast, so biodiesel can be prepared in a small period of time.
- There is no requirement of catalyst in supercritical transesterification process.
- The biodiesel yield in the supercritical method is higher than the traditional transesterification process.
- The separation of fatty esters and glycerol is very easy in the supercritical method as compared to the normal transesterification process also the purification process is also easy.

- The number of step in the supercritical method are less than conventional transesterification process.
- The wastage in the supercritical method is negligible as compared to the normal transesterification process.
- The supercritical method can be used to prepare biodiesel from wide verities of feedstocks.
- This process is better for continuous and fast production.

At supercritical conditions, the liquid fluids possess the properties of both phases i.e. liquid and gas. Furthermore at this condition the density of fluid changes with a higher rate with small variation in temperature & pressure. At supercritical condition solubility properties of fluid also increases. Therefore, at the supercritical condition, the feedstock and alcohol become a single phase due to the higher density of alcohol at higher pressure and temperature. This increases the reaction rate without the use of catalysts. The two main reasons were highlighted due to which the reaction occurs at a very higher rate. The decrease of the polarity of alcohol especially methanol, at higher temperatures and pressure as methanol is a polar liquid. The polarity of methanol almost diminishes at supercritical conditions [170]. Therefore at higher temperatures and pressure, the vegetable oils mixed with polarised methanol as these are non-polarised in nature. The mixing at this condition is homogeneous in nature which increases the reaction rate. The second and important reason is the solubility of vegetable oils and fats enhance with the rise in temperature & pressure. At supercritical conditions, the solubility of triglycerides is high enough to increase the reaction rate [172].

2.6. Optimisation of Biodiesel Production

The production of biodiesel through transesterification process needed alcohol, catalysts, and energy to maintain a constant temperature. The agitation improves the reaction rate according to some research. Therefore, the overall cost of biodiesel depends upon feedstocks' price and expenditure of making. However, feedstock contributes a major portion as compared to production cost which is already discussed. The production cost is not so crucial if biodiesel produced at the laboratory level as it is produces for a small scale. But if biodiesel is produced on the industrial level, the production cost contribution is significant. Therefore to minimise production expenditure of biodiesel, optimisation for the biodiesel production process becomes very necessary. The number of researches did the number of the experiment to optimise production factors of biodiesel production using various optimisation tools [3], [159], [173]–[180]. Singh et al. [174] produce biodiesel from canola oil and the process parameters were optimised using research surface methodology as an optimising tool. According to optimising tools predict the yield of 99% and content of soap was 0.85% while using $KOCH_3$ as a catalyst. On the other hand, the molar ratio for the transesterification was predicted at 4.5:1 w/w. The researcher conducted the experiment as per the suggested parameter by optimising the tool. The researcher found that at this condition the yield is 95.8% while soap formation was 0.75%. The yield gets by the researcher is higher than the maximum yield that he got previously without optimising the tool.

The biodiesel production process can also be optimised by using the Taguchi method. Remezani et al. [181] optimize the process parameters for castor oil biodiesel using Taguchi as optimising tool. The author reported that the yield of nearly 87% can be obtained by taking CH_3KH as a catalyst and the concentration for catalyst (CC) was 0.5%, molar ratio (MR) was 8:1 w/w. By taking all these parameter reactions took 120 min the above mention yield can be obtained from castor oil [159], [181]. However, biodiesel from castor oil was also prepared by

Kilic et al. [159] using response surface methodology as an optimising tool. The author quote that, the yield of 99.81% can be obtained in a shorter period of 10 minutes with 1.5% CC and 7:1 MR. The temperature during the reaction should be maintained at 65°C. The result quoted by Kilic [159] and Ramezani [181] has a large difference and that difference might be due to utilisation of different catalysts for a reaction as the other parameters do not have so much variation.

The catalysts concentration during the reaction is found most important parameters by number of researchers [3], [43], [159], [182], [183]. Bharath et al. [183] optimise the process parameters for pongamia biodiesel by using the Taguchi method. According to Taguchi analysis, the yield of 88.64% to 84.28% can be obtained by taking MR 8:1, reaction temperature (RT) 60°C, 75 minutes for reaction, and CC of 1.5% w/w. however, during the experiment, the author found that the yield of 90.2% can be obtained by taking all the parameters in the above mentioned quantity. The jatropha is one of the oldest feedstocks in inedible oil used in India. Therefore, the experiments on process parameters for the biodiesel production process for jatropha also conducted by various researchers [180], [184]–[186].

Dharma et al. [180] take a mixture of jatropha curcas and ceiba pentandra in equal proportion and prepare biodiesel. The biodiesel production process is optimised by using surface response methodology as an optimising tool. The author chooses Box–Behnken experimental design for optimising the yield during the experiment. The author optimise the alcohol vegetable MR, CC, and mixing speed. However other parameters like RT (60°C) and time of reaction (ToR) (120 minutes) were fixed during the experiment. The author found that the biodiesel yield of 93.3% can be achieved by taking mixing speed 1300 rpm, methanol percentage 30% w/w, and CC of 0.5% w/w. Similar work was conducted by Rashid et al. [187] in which the author optimise the biodiesel production of rice bran oil and the author also used

RSM as optimising tool. The optimise condition of methanol to oil ratio, catalyst concentration, agitation speed, reaction time, and reaction temperature taken by the author was 7.5:1, 0.88% w/w, 600 rpm, 60 minutes, and 55°C respectively. The catalyst used during the experiment was $NaOCH_3$. The author found that at this optimise condition the yield of 83.31% can be obtained for rice bran oil methyl ester.

The literature on biodiesel making optimisation suggested that the higher yield can be obtained at a minimum cost by optimisation. The authors tested the physicochemical properties of prepared biodiesels and concluded that the properties of all biodiesel are within the ASTM standard [18], [66], [188], [189]. The number of literature found in which the authors tested the performance of various biodiesel blends on conventional diesel engine and results were quite impressive [19], [140], [188], [190]–[192].

2.7. Physicochemical Properties of Biofuels

Biofuels are found one of the finest investigations for alternative fuels for IC engines. Biodiesel & bio alcohols are secured in their highest place. But before testing these fuels on the engine, the physicochemical competency of biofuels needs to be tested & the results should be compared with the petroleum diesel fuel. Once the physicochemical competency of biofuels found comparable with mineral diesel than only they can be used in IC engines. The main physicochemical properties that need to be measured are: kinematic viscosity, density, calorific value, cetane number, flash point, pour point, cloud point, acid value, etc. The range of all these properties is fixed for biodiesel under ASTM standard 6751 and that range is already shown in table 2.1 in this chapter. All these properties of various biodiesels and alcohols are discussed in this section.

2.7.1. Kinematic viscosity

The hindrance produced by a layer of fluid to its adjoining stratum during effluence is termed as kinematic viscosity. This property of fluid measured as per ASTM standard D445. The range of kinematic viscosity fixed for biodiesel as per the ASTM D6751 standard is 1.9 to 6.0 mm^3/s at 40°C. Kinematic viscosity reduces as temperature rises for liquids. This is quested that, the kinematic viscosity of most of the vegetable oils is a great deal higher compared with petroleum diesel. Therefore, the oil is transformed biodiesel to detract the viscosity however it is still greater compared to mineral diesel. The viscosity of biodiesel is much greater at a lower temperature, even some of the biodiesels solidify at a lower temperature [193]. The low viscosity of fuel leads to leakage of fuel from the fuel system. However, the higher viscosity of fuel leads to the delay of the mixing process of air-fuel in the intake manifold for spark ignition engine and combustion chamber in the compression ignition engine. The higher viscosity also affects the flow rate of fuel in intake stroke [194]. All this problem occurs with biodiesel.

The kinematic viscosity of alcohol is less than the petroleum diesel engine [114]. The low viscosity of alcohol helps to improve atomisation of alcohol also leads to a decrease in fuel resistance while injected. The lower kinematic viscosity of alcohol leads to shorter ignition interval similitude to mineral diesel [114]. All these properties of alcohol make these a better additive for SI & CI engine. The properties of biodiesel can be improved by blending these with different alcohols.

2.7.2. Density

The density is simply defined as the ratio of the mass of the substance to its volume. The significance of the density of biodiesel and alcohol is the same as carries of kinematic viscosity. The density of biodiesel, diesel, gasoline, alcohol, and other fuels is measured as per the ASTM D941 standard. The density of any liquid fuel is measured by keeping it on fixed temperature i.e. 15°C [195], [196]. The density of the liquid can be represented in terms of specific gravity. The standard fluid in the liquid is water which has a density of 1000kg/m^3. The acceptable range of density for biodiesel as per ASTM D6751 standard is lies between 0.82 gm./cm^3 to 0.9 gm./cm^3[194]. The density of biodiesel is comparable with petroleum diesel. The density of biodiesel of jatropha curcas, soybean, rapeseed, coconut, sunflower, karanja, cottonseed, and waste cooking oil is a higher similitude to petroleum diesel [114]. Whereas the density of biodiesel prepared from orange peel oil, palm oil, kusum oil, etc is lower as compared to conventional diesel fuel [3], [197]–[199]. The density of palm oil is found lowest almost all biodiesel prepared from various feedstocks [197]. Biodiesel has very low calorific value when similitude with mineral diesel therefore the lower density of biodiesel leads to higher consummation of fuel [197].

The density of alcohol is less than petroleum diesel fuel [114]. All alcohol has lower heating value than diesel so fuel consumption of alcohol is higher than petroleum for the same energy requirement. Therefore, the alcohols are used to decrease the density of biodiesel which has greater density similitude to petroleum diesel.

2.7.3. Calorific value

The heating rate of fuel is distinct as the quantity of heat energy released by fuel when it goes for complete combustion in the presence of sufficient air [200]. The calorific value of biodiesel or any liquid fuel is measured as per ASTM D240. The range of calorific value for biodiesel as per ASTM D6751 is not specified as it varies feedstock to feedstock. The bomb calorimeter is utilised for heating rate measurement. The heating rate of all biodiesel is an inferior similitude to mineral diesel [200]–[203]. Furthermore, the heating rate of all alcohol is also inferior to conventional diesel [114], [204], [205]. The poorer heating rate of fuel indicated the lesser energy released during combustion. Therefore the rate of fuel consumption of engine increases.

2.7.4. Cetane number

One of the very crucial properties needful to gauge for fuel of compression ignition engines is termed as cetane number. The cetane number mainly represents the fuel characteristics when it is used in a diesel engine [206]. Higher the cetane number better the fuel for the diesel engine. As biodiesel is utilised as the unconventional energy source for the compression ignition engine, therefore, the value of cetane number plays a very critical role in biodiesel selection [206]–[208]. Although almost all the biodiesels have greater cetane number similitude to mineral diesel. Higher cetane number leads to smoother combustion as it got more time for combustion [206], [209]. Furthermore, the cetane number of all alcohol is less compared to conventional diesel. However, with the upsurge of carbon gratified within alcohol turned to enhancement in cetane number. So higher chain alcohols have greater cetane number similitude to basic alcohols [114].

The cetane number of a fuel depending upon the chain make by fatty acids. The longer is the chain of fatty acids, the higher is the cetane number [210]. The fuel having a shorter ignition delay period has a higher possibility to knock during combustion in the ignition cylinder [203], [210]. The knocking occurs due to a higher ignition delay. Due to higher ignition delay, a large amount of fuel reaches its self-ignition temperature and combust at the same time which causes knocking [3]. Therefore, the higher cetane number for fuel is mandatory which causes smooth combustion inside the combustion chamber.

2.7.5. Flash point

The lowest temperature on which sufficient vapour of fuel can produce that mixed with air and form a combustible mixture is termed as a flash point. The mixture is sufficient to generate a small flame or flame when coming in contact with spark [211]–[213]. Therefore more volatile fuel has a low flash point and difficult to store and transport [214]. The flash point of all the biodiesels has more similitude to mineral diesel. As per ASTM D6751 minimum flash point of biodiesel is 130°C. This makes biodiesel safe to store and transport. On the other hand, the flash point of mineral diesel fuel lies in a range of 60°C to 80°C [48], [215]. The conventional diesel fuel is more volatile which makes it more flammable at room temperature. The flash point of fuels is measured as per ASTM D93 standard. The equipment generally used for measuring flash points is the Pensky-Martens flash point [216].

2.7.6. Cloud point & Pour point

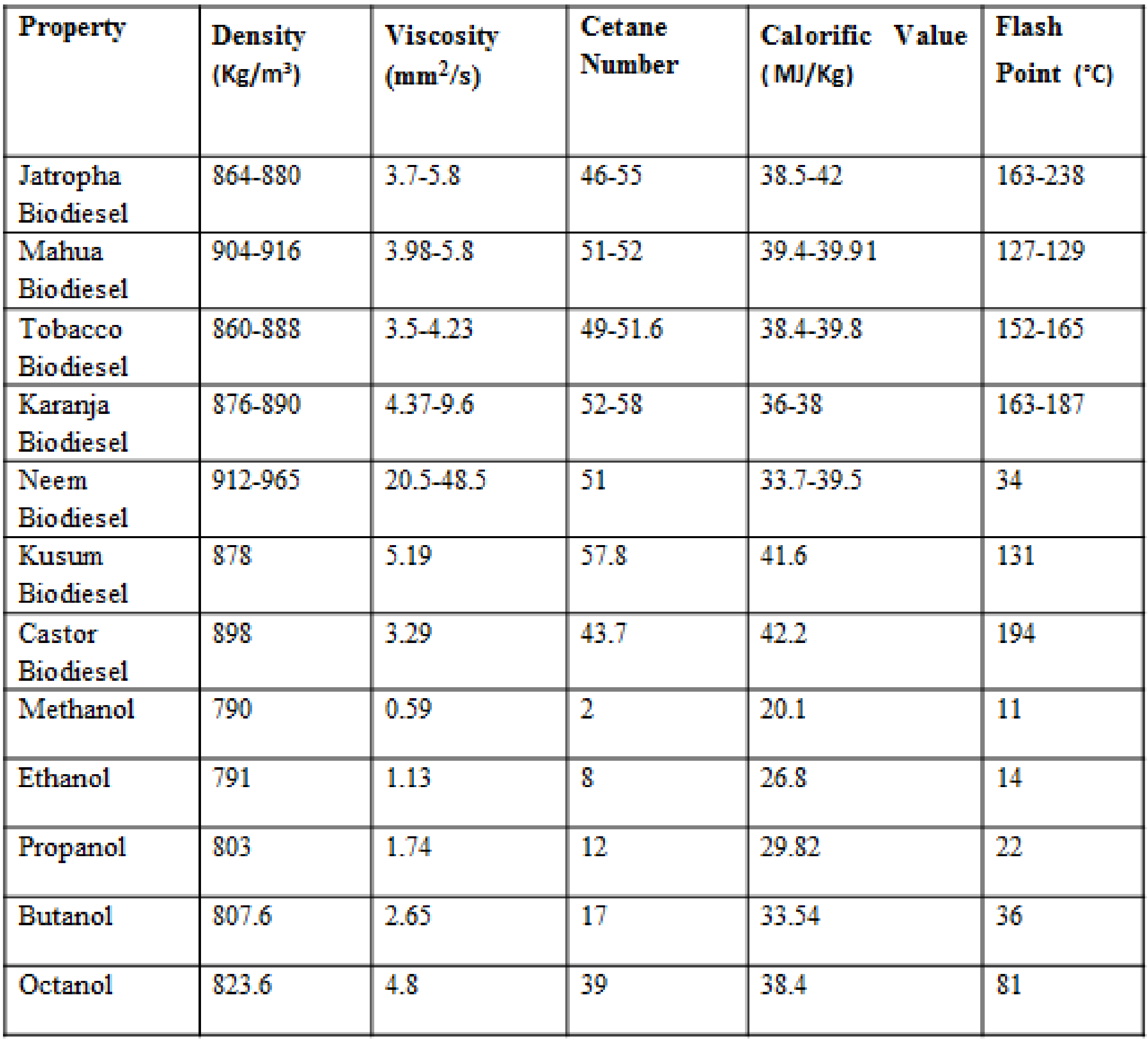
The density of liquid fluid increases with a decrease in temperature. The density is more dominating for biodiesel. At low temperature, some of the biodiesels are solidifying and the density of all the biodiesel increases at a lower temperature [44]. The solidification and partial solidification of biodiesel at a lower temperature can cause blockage of the fuel supply line or jamming of the fuel pump which finally causes the breakdown of the engine. Therefore to avoid these problems the cloud point and pour point need to be tested before using it into a diesel engine. Cloud point represents the temperature at which the first wax crystal of fuel is visible with naked eyes when cooled under controlled conditions. Opposite to this, the pour point represents the temperature at which fuel starts converting into gel [217]. As per ASTM D6751 standard cloud point & pour point range are fixed as -10°C - 17°C & -15°C - 10°Cfor biodiesel. On the other hand, such kind of problem does not occur in alcohol as they have a very low freezing point. Hence the blending of biodiesel with alcohols decreases the overall cloud point

& pour point of blends and improve characteristics of fuel to be used at low temperature condition.

2.7.7. Properties of biofuels

The range of some properties for biodiesel and alcohol is mentioned in the above sections however the values of all these properties are varied in this range only but the value is different for different feedstock. Some important properties of various biodiesels and alcohols are given in table 2.5.

Table 2.5 Important properties of biofuels [45], [50], [73], [80], [142], [159], [198], [218]



Property	Density (Kg/m³)	Viscosity (mm²/s)	Cetane Number	Calorific Value (MJ/Kg)	Flash Point (°C)
Jatropha Biodiesel	864-880	3.7-5.8	46-55	38.5-42	163-238
Mahua Biodiesel	904-916	3.98-5.8	51-52	39.4-39.91	127-129
Tobacco Biodiesel	860-888	3.5-4.23	49-51.6	38.4-39.8	152-165
Karanja Biodiesel	876-890	4.37-9.6	52-58	36-38	163-187
Neem Biodiesel	912-965	20.5-48.5	51	33.7-39.5	34
Kusum Biodiesel	878	5.19	57.8	41.6	131
Castor Biodiesel	898	3.29	43.7	42.2	194
Methanol	790	0.59	2	20.1	11
Ethanol	791	1.13	8	26.8	14
Propanol	803	1.74	12	29.82	22
Butanol	807.6	2.65	17	33.54	36
Octanol	823.6	4.8	39	38.4	81

2.9. Combustion, Performance & Emissions Characteristics of Biofuels

Biofuels are found an attractive unconventional fuel for IC engines while studied their physicochemical properties. However, the properties will not give clarity that fuel performs well or not, while used as an alternative fuel for petroleum liquid fuels. So to get a clear cut picture about their performance in the engine testing need to be conducted on the engine. Number of researchers conducted various research to analyse the combustion, performance & emissions physiognomies of diverse alternative fuels [50], [80], [83], [106], [147], [181], [186], [219]–[221]. The performance of all biofuels discussed in this chapter is analysed in this section by going the number of literature.

2.9.1. Jatropha biodiesel

The density & kinematic viscosity of jatropha biodiesel (JB) is a higher similitude to mineral diesel therefore use of JB in unmodified diesel engine always remain the biggest challenge for the researchers. Varatharajan et al. [222] conducted an experiment using neat JB without and with additives for emission reduction. The author found that the CO and HC emissions of neat jatropha biodiesel are less as compared to the use of jatropha biodiesel with additives. However, the NO_X emissions for neat JB is a higher similitude to results obtained with additives. Similar results are also analysed by Bhupendra et al. [223], [224] and Puhan et al. [106]. As per review done by Thapa et al. [225] blending of JB upsurge the performance of the engine. According to the author review, the brake thermal efficiency can be increased by 0.09% to 2.64% by using up to 20% of jatropha biodiesel blend with petroleum diesel fuel. The author also analysed that, further preferment of JB concentration leads to a decrease in the performance of the engine. Similar results were noticed by Huang et al. [226] and Nalgundwar et al. [227].

Patel et al. [228] investigate the combustion properties of stationary diesel engines and evaluated that the peak in-cylinder pressure is higher while operated with mineral diesel similitude to JB. A similar kind of trend was obtained by Chauhan et al. [229]. However, the exact opposite trend was reported by Gaurav et al. [230]. The contradiction in the result is a matter of bit concern however as per other studies the performance of the engine decreases slightly while running on JB, by considering these studies it can be analysed that the peak pressure for JB should be less than mineral diesel.

2.9.2. Mahua biodiesel

Kapilan et al. [231] carried out an experiment by considering mahua oil biodiesel (MOB) as fuel for an unmodified diesel engine. The author found that the use of neat mahua oil biodiesel leads to abatement of CO, UH & smoke discharges for a diesel engine. However, the BTE of the engine also declines. The author suggested that the blending of mahua oil biodiesel with petroleum diesel up to 20% can make the balance between emissions and the performance of the engine. Comparable effects are shown by Mahalingam et al. [232] and Nayak et al. [233].

Santhosh kumar et al. [234] analyse the combustion, performance & emissions of unmodified diesel engines running on MOB and similitude consequences with a conventional diesel engine. The author found that NO_X emissions for MOB are 6% higher than the conventional diesel engine while operated with full strength. On the other end, the BTE of MOB is a 3.5% lower similitude to normal diesel fuel. The author also noticed that the combustion duration for MOB is more than normal diesel fuel that steerage to greater exhaust gas temperature & increase in NO_X emissions.

2.9.3. Tobacco biodiesel

Usta [235] run the variable speed ratio engine on blends of tobacco biodiesel (TB) & petroleum diesel. The author operates the engine at full load and perceives that blends of TB generate batter BTE compared to a diesel engine. However, the BTE subsidence’s with augmentation in TB proportion in blend after one limit. The author found that with an escalation in engine speed BTE of tobacco biodiesel blend decreases. At 3000 rpm the BTE of blended fuel and petroleum diesel fuel is very comparable. On the other hand at partial loading condition conventional diesel fuel reported better BTE similitude to blended fuel. The tailpipe discharges like CO, SO_2 is less for blended fuel compare to mineral diesel with full throat opening. However, NO_X emissions are less for petroleum diesel fuel similitude to blended fuel at the same loading condition. The same type of trend was observed by Parlak et al. [236] and Mohan Rao et al. [237].

The inside cylinder pressure of the diesel engine was investigated by Mohan Rao et al. [237]. The author perceives that the inside cylinder pressure diesel engine was lower for TB similitude to mineral diesel. The main reason for this is the lower heating value and poor atomization of TB. The author runs the engine on TB with higher injection pressure and advancing injection timing. It was noticed that inside cylinder pressure for TB in this condition is a higher similitude to mineral diesel.

2.9.4. Karanja biodiesel

Chauhan [192]analyse combustion, emissions, and performance analysis of single cylinder fixed speed direct injection diesel engine running of karanja biodiesel (KB) and its blend. The author found that BTE of KB less corresponding to mineral diesel fuel for all loading conditions. In emissions, the CO & HC tailpipe discharge for biodiesel and its blend is scrimp similitude to diesel fuel however NO_X emissions are higher for KB. The neat KB has higher NO_X emission than its blends, the NO_X emissions reduce with the decrease in KB content in the blend. The similar propensity of brake thermal efficiency and NO_X emissions was testified by Agarwal [238]. However, the opposite trend for CO and HC is shown by the author.

The smoke opacity of the unmodified diesel engine is less when used karanja biodiesel as compared to diesel as fuel. both researchers show the same trend [192], [238]. Dhar and Agarwal [239] investigate the performance of KB on the variable speed diesel engine. The author reported that the BTE of engine upsurges with further opening of the throat for KB. The engine reported low BTE at low speed for biodiesel which improves with speed and at 3000rpm the brake thermal efficiency of both the fuels was comparable. Chauhan et al. [240] similitude the peak inside cylinder pressure for KB and mineral diesel for the unmodified engine. The author perceives that inside cylinder pressure for KB is a scanty similitude to mineral diesel. However, due to the shorter ignition delay period of KB, the HRR for JB reaches its peak earlier than mineral diesel.

2.9.5. Neem biodiesel

Sharma et al. [241] compare the combustion, emissions, and performance of diesel engines running on neem oil biodiesel (NOB) with mineral diesel. Similar to the other research the author found that the performance of unmodified diesel engine degrades while powered with NOB as compare to mineral diesel. Further variation in BTE is perceived more at higher load whereas at lower load BTE of both the fuels is comparable. Moreover, CO and HC emissions are noticed less for NOB compare to diesel fuel. However, emissions of NO_X are on the higher side related to diesel on full throat opening. While NO_X proportion in tailpipe outlet is less at no load and low load condition. The same results were also noticed by [242]–[244]. A review study also conducted by Takase et al. [105]. The author analysed the performance of neem oil biodiesel on various compression ratio and speed. The author found that with the increase in speed BTE of the engine is also improves when running on neem oil biodiesel.

The combustion characteristics of NOB was analysed by Sivalakshmi and Balusamy[242] and verdict that the inside cylinder pressure for NOB is a slightly lower similitude to mineral diesel fuel. The combustion of NOB is also started earlier related to petroleum diesel due to the higher cetane index of NOB. The maximum HRR for NOB is a lower similitude to diesel. However, the period for HRR is higher for NOB.

2.9.6. Kusum biodiesel

The kusum oil contains very good properties to use as alternative fuel but till now the use of kusum oil and kusum oil biodiesel is under consideration. Pali et al. [245] perform an experimental study to test combustion, emissions, and performance characteristics of agricultural diesel engines and use the blend of kusum oil biodiesel (KOB) as fuel. The author reported that the efficiency of a stationary diesel engine remains comparable while running at full load with kusum biodiesel and fuel respectively. However, the brake thermal efficiency of the engine reduces by raising the proportion of KOB in amalgam. On the other hand drop in CO & HC emissions was noticed while the engine was running on KOB blends. Meanwhile, NO_X emission for kusum oil biodiesel is higher than mineral diesel on full load conditions. The physicochemical properties of kusum oil biodiesel are found very comparable to petroleum diesel fuel [46], [246].

2.9.7. Methanol

Tian et al. [247] investigate the performance of diesel engines fueled with a mixture of methanol and diesel. The author compares the result with the conventional diesel engine model. The author found that at teeming load BTE of diesel engine observed higher while running on methanol blend however the efficiency decreases by augmenting methanol weightage in fuel.

The author also measured the emissions of the diesel engine fuelling with methanol blends. The NO_X, CO & HC emissions of the diesel engine at full load are less while running on methanol blends. The similar results also analysed by Kumar et al. [248], Data and Mandal [249], Abdullah [250], and Wang et al. [251]. Tian et al. [247] nay analysed the influence of speed of engine on demeanor when running on methanol blends. The author found that with increasing speed as well as the trend of performance & emission of the engine remains the same. Increasing methanol content more than 20% put some contrary influence on the performance of the engine as calorific value and cetane number of methanol is a much poorer similitude to diesel fuel.

Akasyah et al. [250] conducted the experiments on diesel engine operating with methanol on various operating speeds. The author found that inside cylinder pressure for methanol is a much higher similitude to mineral diesel for all engine speeds. However, HRR is much lower for methanol for the entire speed range. According to the author perceives, the ignition delay period is shorter for methanol similitude to diesel however cetane index of methanol is much lower compared to mineral diesel.

2.9.8. Ethanol

The heating value & cetane number of ethanol is a better comparison to methanol, so as per of properties analysis it can be assumed that ethanol will give better results as compared to methanol. Xingcai et al. [252] investigate the performance of diesel engines powered with diesel & ethanol blends and compare the result with the conventional diesel engine. The author found that BTE of the diesel engine was better while running on ethanol blends compared to the conventional diesel engine, especially at higher load. The author also found that at lesser speed BTE of the engine decreases as compared to the normal operation mode. But with an increase in engine speed, the ethanol blends containing up to 20% ethanol perform better than mineral diesel fuel. The tantamount results are quoted by Tian [247] and Jamrozik[253].

Tian et al. [247] also investigate the emissions profile of diesel engine powered with ethanol and diesel blends. The author found that emissions of the engine reduce while operating with ethanol mixture compare to mineral diesel. The emissions which reduce include CO, HC, and NO_X. The emissions of the engine remain less throughout the loading conditions and for all speeds. The number of researchers uses ethanol, biodiesel & diesel mixture as fuel to check the combustion, emissions & performance of the unmodified diesel engine [254]–[256].

2.9.9. Butanol

The butanol contains a higher carbon chain which enhances the properties like calorific value and cetane number. The higher heating value and higher cetane number of butanol make it better fuel for a diesel engine as compared to methanol and ethanol. However, the cost of butanol is slightly higher than these two basic alcohols. Sinha and Kumar [80] examine the performance of unchanged diesel engines taking jatropha biodiesel & butanol blend as fuel and juxtaposition outcomes with a conventional diesel engine. The author found that the blending of butanol in jatropha biodiesel enhances the combustion characteristic of the fuel and results in better performance of the engine. The blending of butanol also improve the emissions characteristics of the engine and result in lower CO, HC, and NO_X emissions than jatropha biodiesel. However, the exhaust of tailpipe is marginally lower, except NOx, juxtaposition conventional diesel mode. A similar trend is observed by Ibrahim [257].

Karabektas and Hosoz [77] investigate the performance & emissions of a diesel engine with the iso-butanol-diesel mixture. The author found that BTE of diesel engine declines with an upsurge in butanol content in the blend. However, the emissions like CO and NO_X are found less foe diesel-butanol mixture compare to mineral diesel. The HC increases slightly for the blend. Zheng et al. [258] investigate the combustion performance of biodiesel and n-butanol blend in diesel engines and found that the inside cylinder pressure curve shows a higher peak in the case of n-butanol blend similitude to biodiesel and diesel curve. The HRR of the n-butanol blend is higher compared to biodiesel. However, the ignition delay period increases while adding n-butanol in biodiesel but the combustion of prepared fuel improves. A similar trend is also represented by Liu et al. [73] and Lapuerta et al. [195].

2.9.10. Octanol

Octanol is the higher carbon alcohol containing 8 carbons in one molecule. This further proliferation cetane number & heating value of alcohol. Rajesh Kumar [89] evaluate diesel engine performance on operating with diesel-octanol blend & compare the result with mineral diesel. The researcher found that BTE of diesel engine improves when operated with the diesel-octanol blend. The BSFC decreases for the same operation mode. The author found that this occurs due to comparable heating value & cetane number of octanol. The author also found that the emissions of the engine like CO, $NO_{X,}$ and smoke also decreases with the diesel-octanol blend. Similar kind of results was reported by Sinha and Kumar [80] and Ashok et al. [204] when operating the engine with biodiesel and octanol blends.

Nour et al. [259] evaluate the effect of mixing of octanol with diesel on the combustion of fuel in the diesel engine. The author perceives that mixing of octanol in diesel leads to higher peak inside cylinder pressure and better combustion of fuel at a higher speed. However, at a lower speed, the mixing of octanol is not so effective. The author also noticed that the addition of octanol leads to longer ignition delay that causes a delay in HRR w.r.t. crank angle rotation and peak inside pressure achieve after TDC. This might because a decrease in the performance of the engine at lower engine speed but at higher engine speed performance of engine improves.

Similar results are obtained by Kerschgens et al. [93] while conducting a simulation study on diesel engine combustion running with the n-octanol mixture.

2.10. Outcomes of the Literature Review

As a conclusion of the extensive literature review to study of replacement of mineral diesel by biofuels, biodiesel production, optimization, performance, emission and combustion analysis of small capacity diesel engine fuel with biofuels and blends. The following foremost conclusions can be drawn;

1. As a conclusion of the extensive literature review to study of replacement of mineral diesel by biofuels, biodiesel production, optimization, performance, emission and combustion analysis of small capacity diesel engine fuel with biofuels and blends. The following foremost conclusions can be drawn; Most of the energy requirement is full fill by crude oil which becomes the biggest concern for the world, as fossil fuels are diminishing. The replacement of fossil fuel with sustainable fuel is the need of time.
2. Biofuels have the potential to substitute for mineral diesel.
3. Most of the literature suggested that SVO cannot be used in CI engines due to higher viscosity and higher density. It can be addressed by a reduction of viscosity of SVO i.e. micro-emulsion, pyrolysis, blending, and transesterification. Transesterification is the most convenient process in which biodiesel can be produce from SVO and the characteristic of fuel is also improved.
4. Biodiesel produced by a different method in which ester and Glycerol are separated from vegetable oil. The two-stage transesterification is a very common method for the production of biodiesel. Biodiesel is produced from edible oil, inedible oil, and animal fats. Biodiesel production from edible oil creates competition food versus energy, hence. Globally, attention on inedible vegetable oil is drawn. Jatropha is regarded as one of the best options for biodiesel production in tropical and subtropical developing countries.

5. To make the commercial production of biodiesel economical and competitive needs production parameters optimization is required for increasing the yield.
6. Mostly literature shows that the use of neat biodiesel, improvement in emission except for NOx but decrement in BTE but some researchers show mixed response lower NOx emission and higher HC emission and Smoke opacity of biodiesel compare to diesel. While some exhibited that the use of blends of biodiesel with diesel, improvement of BTE, and emission compared to diesel and neat biodiesel.
7. Most of the researcher agreed that use of lower alcohol reduces the viscosity of biodiesel and improve the combustion of biodiesel as well as NOx emission but reducing the BTE. But nowadays the use of higher alcohol with a blend of biodiesel can overcome the drawback in the use of lower alcohol.
8. The blending of alcohol increases the ignition delay, affecting reduction in residence time of combustible mixture inside of the cylinder, subsequently in NOx reduction.
9. Literature has shown that the blending of higher alcohol enhanced the incylinder pressure, HRR, and mass fraction burn rate in the diffusion state.

2.11. Research Gap Analysis

On the base of exhaustive literature review, the following research gaps were recognized.

1. A lot of performance and emission tests have suggested either increase or decrease in BTE with the reduction in CO, HC emissions when engine fuel with a blend of biodiesel and diesel or neat biodiesel. NO_x has been found to increase in most cases, many technics have been used for controlling the NOx emission but most of them conceding the BTE. Due to strong norms of emission and energy efficiency compel the researcher to explore such that blend of biodiesel which able to reduce the overall emission without compromising the BTE of biodiesel.

2. Biodiesel is currently utilized as an extender fuel in the CI engine. However, the potential substitute for mineral diesel is still undetermined.
3. The main concern of BS-VI emission is NOx emission. The use of Biodiesel generates more NOx. Reduction of NOx emission without compromising of BTE yet to be explored.
4. Most work is carried out on performance analysis and emission of a blend of lower alcohol with biodiesel or diesel and biodiesel but the blend of biodiesel with higher alcohol is not fully explored.
5. It is also worth mentioning that blend of various higher alcohols namely n-butanol, propanol, pentanol have been carried but very few works are carried out of n-octanol blend with biodiesel
6. Limited quantum of work has been reported on combustion analysis and Combustion characteristics based on heat release models and mass fraction burned model of engines running on a blend of higher alcohol n-octanol and biodiesel.

2.12 Problem Statement

In light of wide-ranging literature assessment and pinpointing the research gap it was concluded that utilization of biodiesel is a favourable substitute for petroleum diesel, but the main barrier of use of biodiesel is production cost it can be minimised by optimisation of biodiesel production yield. The use of biodiesel decrement of BTE and increment of NOx was observed. To mitigate the obstacle of the use of biodiesel, the addition of renewable higher alcohol in biodiesel may offer a prospective solution.

Therefore, exhaustive engine trials using a blend of n-butanol and n-octanol with Jatropha biodiesel in various proportion and subsequently analysis of performance, emission and combustion may provide adaptability of the blend. Which may provide, likely substitutes for replenishing the fossil diesel.

2.13 Research Objective

The following objectives were contemplated for present work.

1. Exhaustive literature review. To find out the potential use of renewable fuel in the unmodified compression ignition engine.
2. Identification of unutilized oil feedstock and higher alcohol.
3. Production and Optimization of production process parameter for yield production of biodiesel.
4. Preparation of biodiesel and n-butanol and biodiesel n-octanol blend in the different ratios.
5. Determination of important physicochemical properties of biodiesel, n-octanol, and n-butanol and their blends and mineral diesel.
6. Development of experimental diesel engine test rig to full fills the research requirement.
7. Conducting exhaustive experiments on the test rig to evaluate performance, emission characteristics of the blend of biodiesel and n-butanol, biodiesel, and n-octanol blend and compared with base fuel biodiesel and diesel.
8. Evaluation of the effect of blending of higher alcohols with biodiesel on performance and emissions including evaluation of combustion characteristics with different test fuels with the help of P-Ө and heat release rate diagram on single cylinder water cooled diesel engine.

CHAPTER 3

SYSTEM DEVELOPMENT AND METHODOLOGY

3.1 Introduction

The current chapter contains the procedures followed during the research. This chapter explains how research is conducted. This chapter also explains the working principles of all the instruments used during the research. The step wise explanation of all procedure is as follows:

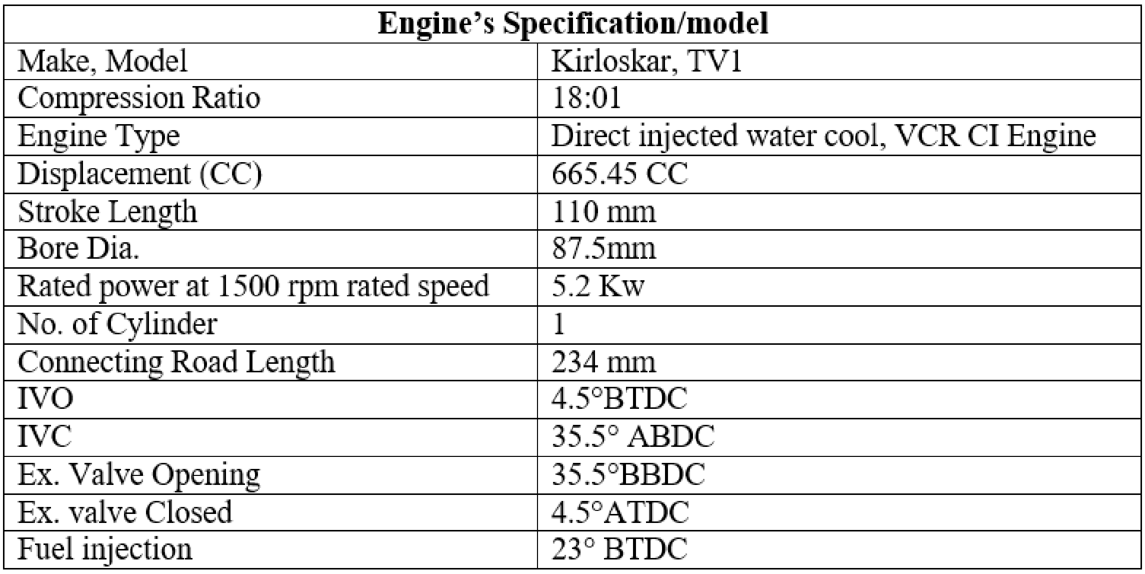
- Selection of Engine
- Selection of Fuel
- Preparation of Fuel.
- Characterization of Fuels.
- Engine Test Rig.
- The test fuels are analysed based on their performance on the diesel engine.

After going through the number of research articles, it is found that self-sustainability in the fuel especially in the rural area is desperately required. It is found that plenty of work has been done on Jatropha but still it is away from self-sustainability. The biodiesel was prepared from Jatropha oil also process optimization was done for biodiesel production. The blends of JOME with n-butanol and n-octanol were prepared also the physicochemical properties of all test fuels were measured before testing them in the engine. The blends were tested on the engine where performance, combustion, and emissions characteristics of the engine was analysed. All the methods of fuel production, testing with all types of equipment used during the current research are explained during the chapter.

3.2. Engine’s Selection

Most of the farmers in rural regions are using constant speed stationary diesel engines for agriculture. In the present research Kirloskar stationary, single cylinder, four strokes with a direct fuel injection system, and constant speed engine was selected. This is a water-cooled light duty engine which makes it very popular among farmers due to its simple design and economical operation. To provide enough strength to the engine, the engine cylinder is made up of cast iron. The specifications of the engine used in current research are given in table 3.1.

Table 3.1: Engine’s specification



Engine’s Specification/model	
Make, Model	Kirloskar, TV1
Compression Ratio	18:01
Engine Type	Direct injected water cool, VCR CI Engine
Displacement (CC)	665.45 CC
Stroke Length	110 mm
Bore Dia.	87.5mm
Rated power at 1500 rpm rated speed	5.2 Kw
No. of Cylinder	1
Connecting Road Length	234 mm
IVO	4.5°BTDC
IVC	35.5° ABDC
Ex. Valve Opening	35.5°BBDC
Ex. valve Closed	4.5°ATDC
Fuel injection	23° BTDC

3.3. Selection of Fuel

The fuel selection is done on the availability, properties, storage, and most important parameter on its self-sustainability. The main aim of the present research is to make rural farmers self-sustainable. Hence, the selection is done by keeping that aim in mind. The biodiesel prepared from jatropha oil was found a suitable option for that as a large amount of work is done on it but still fails to make it use commercially. Jatropha is easily available and most important it is nonedible. After going through a number of research articles it is found that jatropha oil, as well as biodiesel prepared from it, are remain stable for a longer time and easy to store as well. But after analysing the properties it was observed that it is very difficult to use JOME directly to the unmodified diesel engine due to its high viscosity. Hence, the viscosity of JOME should decrease either by preheating or blending. Blending with petroleum diesel which goes away from the self-reliability objective. Therefore, some other renewable fuel is required which decreases the overall viscosity of the blend without changing properties of fuel much. Hence, higher alcohol is found as the most suitable option for that. The properties of all higher alcohols are studies with the availability and renewability and found that n-butanol and n-octanol is the better option among all alcohols.

3.3.1. Straight vegetable oil Jatropha

The seed from the jatropha plants was collected to extract the jatropha oil from them. Jatropha plants are available everywhere now a day but the origin of jatropha plants was from America. The jatropha plant can be grown in all types of weather and soils. But the most favorable soil is soft soil where it can grow at a faster rate. The jatropha plant is found nonedible but it has multiple uses. The jatropha plant grows at a very fast speed and also produces fruit in the early stage of life. It was found that the jatropha plant starts producing seeds after 2 years from the plantation. However, the first production needs to be clip before maturation which was helpful to grow the plant at a good rate and strong enough. The jatropha plant is very useful for erosion control of sand when it planted across hills. Also as discussed its growth is very fast hence it might help many countries in resolving their deforesting problems. The non-edibility of the jatropha plant helps to keep animals away from the forest. However, jatropha is inedible but its leaves can be used in the number of medicinal purposes. The outer cover of the fruits can be used for producing fire in the rural area and producing methanol or biogas for industrial as well as commercial purposes. The fruit hulls can also be put on the land which helps the soil to full fill the requirement of nutrients. The jatropha plant, jatropha fruits, jatropha seeds are shown in figure 3.1.

Figure 3.1: Jatropha curcas plant and seeds.

The jatropha seed can be used to produce jatropha oil, seed shell, and seed cake. The jatropha oil can be directly used as fuel for cooking and lightings. The jatropha oil can also be used as a lubrication purpose at several places. The seed cake can be used as fertilizer in agriculture. As it has properties of oil that contain some insecticide, hence it gives power to the soil to fight against some specific disease. The seed cake has some active bacteria which enhance the rate of anaerobic digestion in the biogas plant.

The jatropha oil has high viscosity and stickiness due to which it cannot use as fuel in internal combustion engines. As it is a good source of renewable energy due to its higher yield, high caloric value, and high cetane number. To reduce the viscosity and stickiness the biodiesel can be prepared from the jatropha oil which can use directly in an internal combustion engine with a small modification in the engine and can be used directly without modification by blending with petroleum diesel fuel. The properties of JOME were found very comparable to petroleum diesel fuel. The combustion of JOME in diesel engine produces nearly zero emissions as compared to petroleum diesel fuel as its plant consume more CO_2 as produce by JOME during combustion.

3.3.2. Biodiesel Production

The most common method of producing biodiesel from vegetable oil and waste fats is a transesterification process. During this method the fatty acid of vegetable oil, waste cooking oil, animal fats, etc. react with alcohol like methanol and ethanol in the catalytic environment at suitable temperature and form esters of fatty acid which is commonly known as biodiesel. Transesterification is mainly divided into two basic categories i.e. single stage transesterification and double stage transesterification process. The biodiesel can be produced through a single stage transesterification process only when the free fatty acid (FFA) content of fat is found less than 2% theoretically. Further, if FFA value is more than 2% of two stage transesterification is performed to prepare biodiesel. The two stage transesterification process carried two stages, in the first stage, the FFA of oil is reduced to less than 2%. This process is known as the esterification process. After the esterification process, the biodiesel of the reduced FFA oil is prepared using the normal transesterification process. The complete process of biodiesel production is explained in detail in this section. The flow chart of biodiesel production is given in figure 3.2 and the process of biodiesel production is presented in plate 3.1.

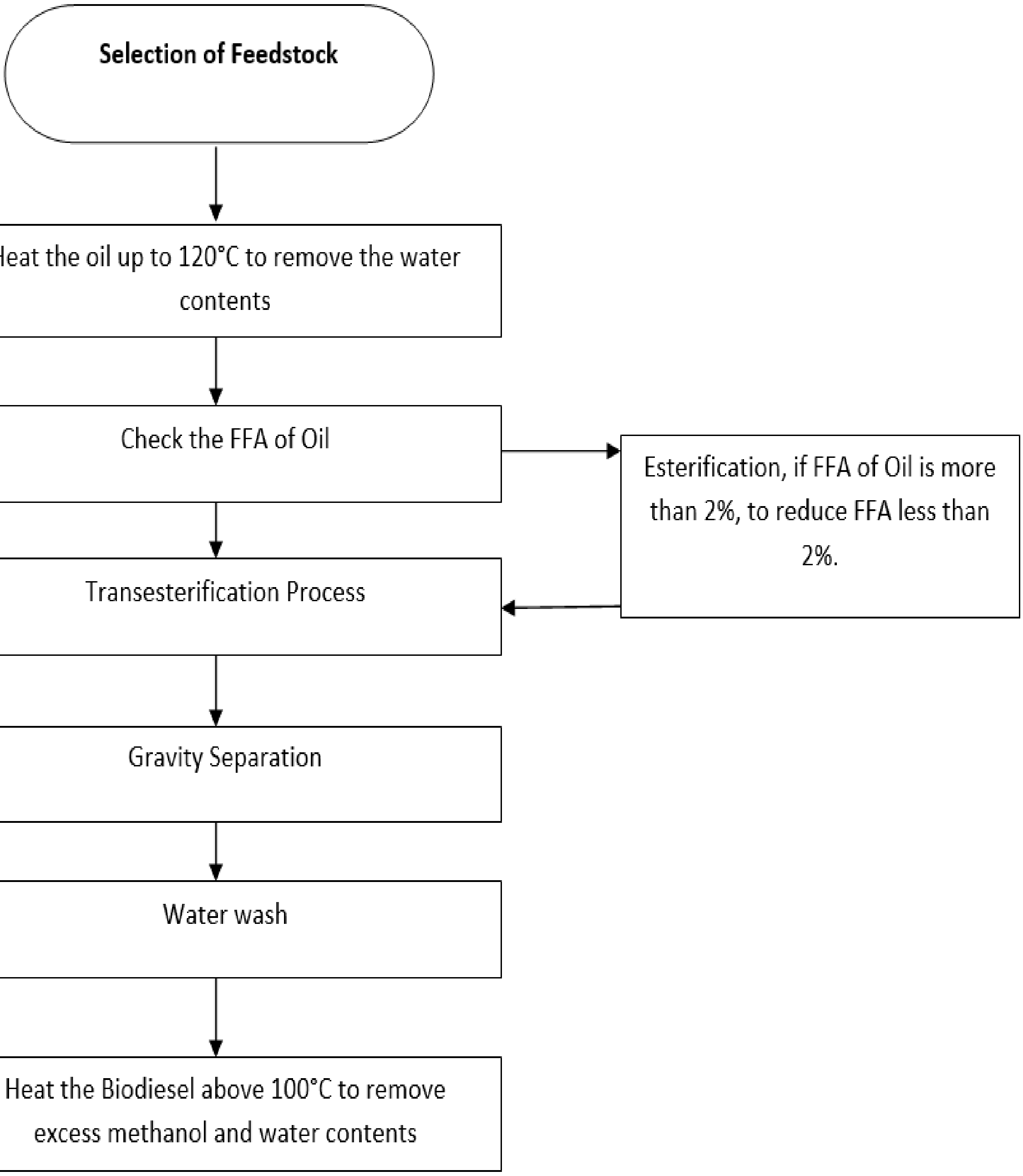


Figure 3.2: Biodiesel production flow chart

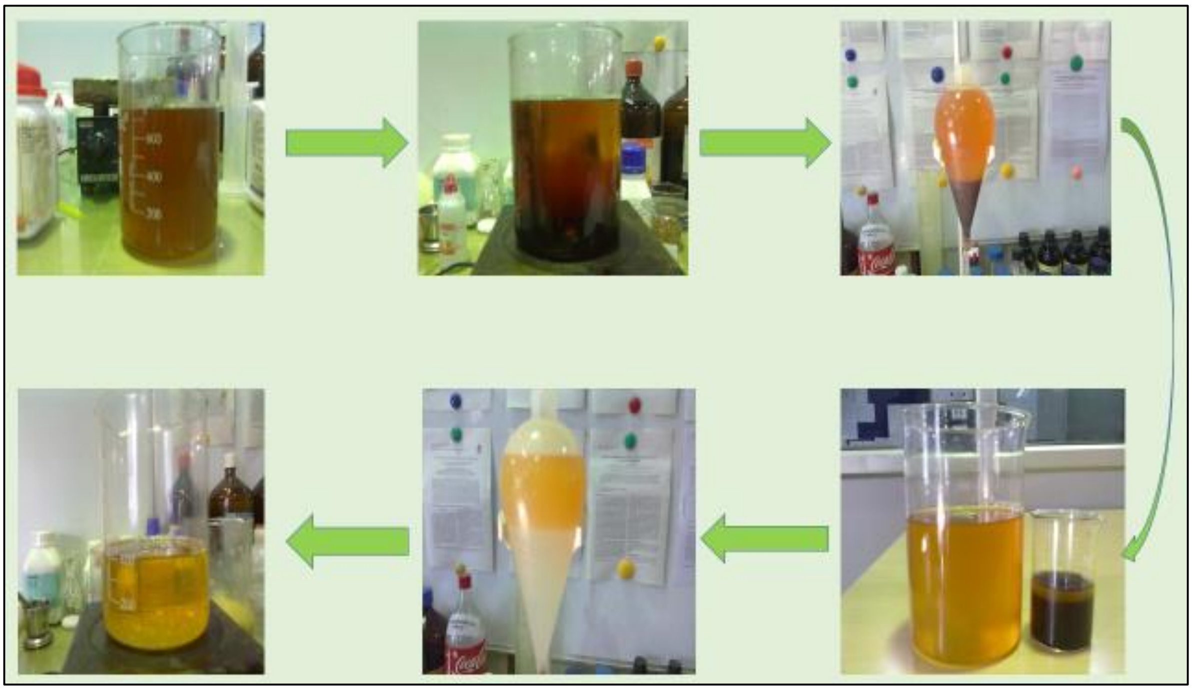


Plate 3.1: Process of biodiesel production.

3.3.2.1. Acid number

The acid number is also known by acid value and neutralization value. The acid number can be defined as the milligrams mass of either sodium hydroxide or potassium hydroxide utilized to neutralize the free fatty acid present in one gram of oil. The acid number of oil was determined in the CASRAE, DTU. To determine the acid number, one gram of oil is mixed with 10ml of methanol in a small beaker. Two drops on phenolphthalein as an indicator was also added in the solution. The prepared solution was then titrated with potassium hydroxide having a normality of 0.1. The potassium hydroxide was added into solution drop wise until the solution gets a light pink colour and it remains at least for 30 seconds. The quantity of potassium hydroxide (KOH) utilized during the process was measured from the burette. The acid number is then calculated with the help of the following formulas:

$$\text{Acid Value} = \frac{56.1\,VN}{M}$$

Where,

56.1= Molecular weight of KOH

V= Volume of KOH consumed (in ml)

N = Normality of KOH solution (0.1 in present research), and

M= Mass of oil (in g)

3.3.2.2. Free fatty acid

The free fatty acid, also known as FFA in short, is calculated after calculation of acid number. The formulas can be used for FFA calculation are as follow:

$$\text{FFA (\%)} = (V_T\text{-}b)\,\frac{28.2\,N}{M}$$

Where:

28.2= Molecular weight of oleic acid

V_T= Volume of titrant,(in ml)

b= Blank volume

N = Normality of KOH solution (0.1 in present research), and

M= Mass of oil (in g)

OR

$$\text{FFA (\%)} = \text{Acid Number}/1.99$$

3.3.2.3. Esterification

The FFA of the jatropha oil can be reduced by the esterification process. If the FFA of the oil is more than 2%, the saponification process becomes more dominating than the transesterification process due to the free availability of short bonds in the oil. Hence, soap form instead of esters of oil. Therefore, the FFA of oil needs to be reduced below 2% before going for the transesterification process. In this process, the oil was heated above 100°C for

10-20 minutes to remove moisture content so that it does not affect the reaction process. After heating the oil was cooled down to 60°C as methanol is used for esterification which has a low boiling point (65°C). If the temperature during the reaction is more than 65°C, methanol starts evaporating and the exact oil to methanol molar ratio becomes difficult to calculate. The oil was put in a round neck flask in which reaction takes place. A manually controlled magnetic stirrer with the heating pad was used for the reaction so that the temperature and stirring speed can be controlled during the reaction. The round neck flask was then put on the magnetic stirrer. A magnetic bit is kept inside the flask for continuous agitation. As discussed above the temperature was maintained at 60°C and stirring speed was fixed at 250 rpm throughout the reaction. A mixture of para toluene sulphuric acid (PTSA) and methanol by taking in 0.5% w/w and 10% v/v respectively is prepared in a small beaker. The prepared mixture is then fed into the flask in small quantities at regular intervals. Close the flask with tight cork to avoid evaporation of the methanol. A sample of 1 gm. of the solution is taken from the flask at a regular interval of time for measuring the FFA of the oil. Wait for 30 min so that the reaction complete effectively and check the FFA of solution. If the FFA of the solution does not come less than 2% repeat the esterification process until the FFA comes less than 2%. The reaction performed during the esterification process is given as follows:

$$R_1\text{-COOH} + ROH \xleftrightarrow{H^+} R - O - CO - R_1 + H_2O$$

Where:

R_1COOH: Carboxylic Acid

ROH: Alcohol

R-O-CO-R_1: Esters

H_2O: Water

3.3.2.4. Transesterification

The biodiesel is produced through transesterification and the process is well known worldwide. During this method, the oils and fat are reacted with an alcohol to enhance the reaction catalysts are also used. During the reaction, fatty acids are converted into fatty acid methyl ester which is also famously called biodiesel. The transesterification process is classified into two categories based on the catalysts used.

a) Alkaline catalyst transesterification
b) Acidic catalyst transesterification

The process followed in both methods is the same except the nature of catalysts. The yield in alkaline catalyst transesterification is less when compared to the yield obtained through acidic catalyst transesterification. However, reaction time and the reaction temperature are less in alkaline catalyst transesterification. The temperature required in acidic transesterification is around 60°C and the time required for completion of the reaction is around 3 hours which is much more than base transesterification. Hence, due to the higher time, the acidic transesterification becomes expensive.

The base transesterification process has opted for the present research work. In which methanol was selected as alcohol and KOH was used as catalysts. For biodiesel production, the oil having FFA less than 2% is first heated above 100°C to remove water and extra methanol present in the oil left with only pure oil. The oil is then cooled down to 50-60°C, this temperature is the same on which reaction takes place. Meanwhile, the solution of methanol and KOH was prepared in a separate beaker. For the solution, the molar ratio of methanol to oil is taken in the range between 3:1 to 9:1 while the catalyst concentration keeps in between 0.5% to 1.5%. The solution of methanol and KOH is pouring into the oil at a regular interval of time in small quantities. The transesterification reaction takes time hence the reaction beaker is kept on the continuous agitator. The heating pad with a magnetic stirrer was used for that so that the constant speed agitation and constant reaction temperature can be maintained during the reaction. The reaction time varies between 30 minutes to 120 minutes depending upon the quality of the oil. Hence after 30 minutes, the solution needs to check whether the reaction completed or nor by turning off the agitation for 2 minutes. This process keeps on repeating every 15 minutes. The step-wise reaction was discussed in chapter 2.

Once the transesterification reaction completed, the solution was put into separating funnel in which gravity separation takes place. The gravity separation takes nearly 20 hours hence the solution keeps for gravity separation for one complete day. After one day two layers were observed in the separating funnel. The bottom layer was dark in colour which is the layer of glycerol and the upper layer was having a light colour which is the mixture of biodiesel, methanol, and a small quantity of glycerol. Remove the lower layer of glycerol by opening the valve of separating funnel. Now to remove the extra present glycerol and methanol in the biodiesel water treatment process need to be performed. In this process, the biodiesel left with gravity separation was mixed with warm water taking in 40% v/v. the solution of water and biodiesel was mixed well and then put for gravity separation again for some time. This time, the time taken by the process is very less than take in the first stage. Similar to the previous process, two layers formed in this process as well out of which lower layer is whitish in colour which is the mixture of water, methanol, and glycerol and the top layer contains biodiesel and methanol. Repeat the process until the bottom layer contains pure water in the separating funnel. Once all glycerol remove from biodiesel, heat the biodiesel at the temperature of 120°C for at least 30 minutes to ensure that the water formed during the reaction and extra menthol present in biodiesel get evaporated and only pure biodiesel left inside the container. The biodiesel reactor having capacity 10 litres is represented in plate 3.2.

Plate 3.2: Biodiesel reactor.

3.3.3. Optimization of Biodiesel Production

In this section, the process of biodiesel production is optimized. As discussed earlier, transesterification is very famous and most used among all biodiesel production process. In transesterification, the triglyceride (like vegetable oil, waste cooking oil, animal fats, etc.) reacts with alcohol in the catalytic environment at a suitable temperature and produce fatty esters and glycerol, that fatty esters are famously known as biodiesel. Therefore the rate of biodiesel production and yield depends upon catalytic concentration oil alcohol molar ratio and temperature of the reaction. If the main focus in biodiesel production is only on yield and economy of the process then some factors that affect these are oil alcohol molar ratio, catalyst concentration, the temperature of the reaction, time of reaction, agitation speed, etc. All these parameters affect the cost of biodiesel directly and indirectly. Therefore to reduce the production cost and time and overall cost of biodiesel production, the process parameters need to optimize first. To optimize all process parameters, the number of experiments was to perform and the results have to analyse. This method is time consuming also having very little accuracy due to its limitations. Therefore it is better to use some optimization techniques which decrease the number of experiments and give very accurate limits of parameters.

The number of optimization techniques is used by various researchers to optimize the biodiesel yield and reduce the overall cost of the process [3]. All off the optimization techniques, response surface methodology (RSM) is gaining popularity due to its simplicity, accuracy, and effectiveness [3]. In RSM also, the central composite design (CCD) model is mostly used for biodiesel production. The CCD model is an experimental based model and composed of factorial design having a class of 2^k factorial. Here the number of variables is represented by “k”. Each variable has its significance and the upper and lower limit of the variable is provided in the starting.

3.3.3.1. Optimization of the esterification process

The difficulty increases for the biodiesel production process if the FFA content of oil and fat is higher than the desired level. As discussed in the earlier section that the biodiesel is produced in two stages in such conditions. Out of two stages, the first stage is for FFA reduction, in which FFA is bringing at the count of less than 2%, and the process is known as the esterification process. The FFA of JO is much higher than 2% therefore, esterification needs to perform before the transesterification process. The esterification process is performed nearly similar to the transesterification process except for the change in the catalyst. Therefore it is also important to decrease the FFA of jatropha oil and process parameters are optimized for esterification as well. There is the number of parameters (catalyst concentration, molar ratio, reaction time, agitation speed, reaction temperature) that affect the esterification process, but four parameters i.e. molar ratio, reaction temperature, catalyst concentration, and reaction time was selected for optimization process [3]. The agitation speed does not affect the esterification process so much, that’s why the agitation speed was not considered for the optimization process. A total of 30 sets of experiments were suggested by the software (Design Expert) as per factorial points, axial points, and central points [3]. The formula given below is used to calculate the number of experiments performed for optimization.

$$N = 2^k + 2k + N_o$$

Where,

“k” represents independent variables which are 4 in number in the present study;

“N” number of repeated experiments which is 6 in number.

Set of experiments suggested by RSM to optimize the esterification process of jatropha oil are shown in table 3.3. However, the range of all parameters for esterification optimization is given in table 3.2. The set of experiments contains 23 different experiments having a different value of parameters and 6 experiments are repeated.

Table 3.2: Process Parameters with their ranges for esterification of Jatropha oil

Name	Factor	Units	Low Level	High Level
Catalyst concentration	A	% (w/w)	0.5	1.5
Reaction temperature	B	℃	45	65
Time	C	Minutes	30	90
Molar Ratio	D	Methanol/oil	3	9

Table 3.3: Design matrix for esterification of Jatropha oil

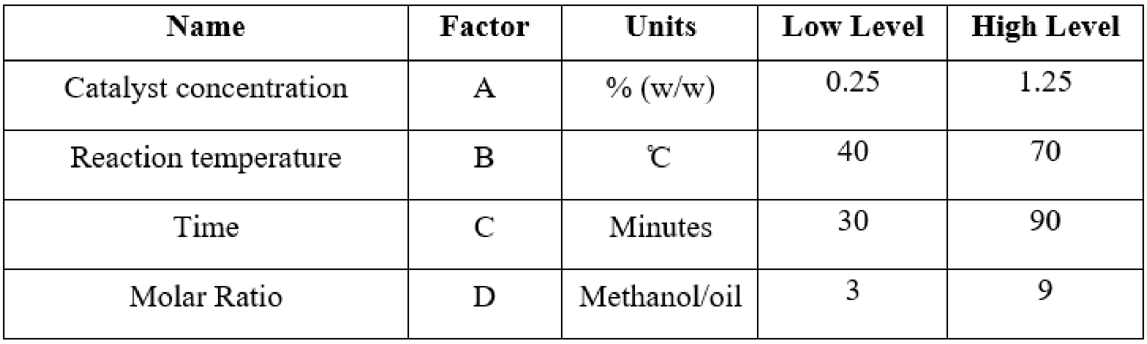
Run	A:Catalyst Concentration	B:Reaction Temperature	C:Reaction time	D:Molar Ratio
	%(w/w)	^{0}C	Minutes	Methanol/Oil
1	0.5	45	90	9
2	0.5	65	30	9
3	1.5	65	90	3
4	1	55	60	12
5	1	55	60	6
6	1.5	45	90	9
7	0.5	45	30	9
8	1.5	45	30	3
9	2	55	60	6
10	0.5	65	90	9
11	1	75	60	6
12	1	55	60	0
13	0.5	65	30	3
14	1	55	60	6
15	1	55	0	6
16	1.5	65	30	3
17	1.5	65	30	9
18	0.5	45	90	3
19	0.5	65	90	3
20	1	55	120	6
21	0	55	60	6
22	1.5	65	90	9
23	1	55	60	6
24	1	35	60	6
25	0.5	45	30	3
26	1.5	45	30	9
27	1	55	60	6
28	1	55	60	6
29	1.5	45	90	3
30	1	55	60	6

All the suggested sets of experiments are conducted in the CASRAE and the result is put back in the software to get parameters value for esterification optimization. The one optimized set of experiments is then suggested by the software which shows that the FFA of jatropha oil can be abridged to 1.7% from 7.1% by taking those values. The detailed results of the esterification process are presented in the result and discussion section.

3.3.3.2. Optimization of the transesterification process

The second step in biodiesel production of high FFA content oil is the transesterification process which is the main process of biodiesel production. During this process, oil or fat reacts with alcohol and produces biodiesel through a chemical reaction in the presence or absence of catalysts. As discussed earlier the esterification and transesterification processes are nearly similar to each other just change in the catalyst used for the reaction. However, the upper and lower range of the parameters may change in this process as this process is used to optimize the yield of biodiesel production. Therefore a low FFA solution is used to prepare biodiesel of jatropha oil. The range of all the parameters was entered into the software after that the software gives several sets of experiments to conduct. The range of parameters entered into the software is given in table 3.4 and table 3.5 shows the number of experiments suggested by the software.

Table 3.4: Process parameters with their ranges for transesterification of jatropha oil



Name	Factor	Units	Low Level	High Level
Catalyst concentration	A	% (w/w)	0.25	1.25
Reaction temperature	B	℃	40	70
Time	C	Minutes	30	90
Molar Ratio	D	Methanol/oil	3	9

Table 3.5: Design matrix for transesterification of jatropha oil

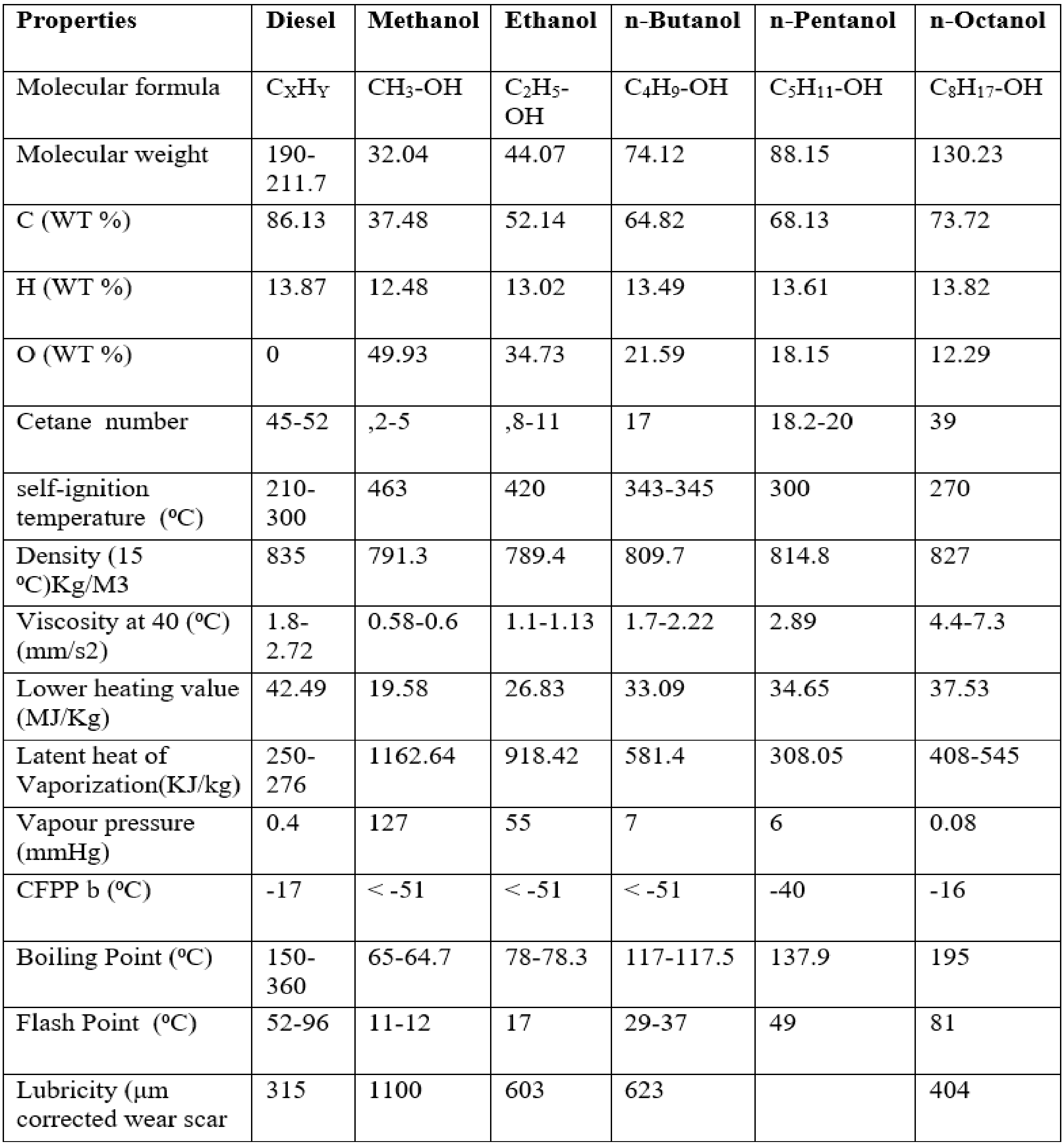
Run	A:Catalyst concentration	B:Reaction Temperature	C:Reaction Time	D:Molar Ratio
	%(w/w)	^{0}C	Minutes	Methanol/Oil
1	0.25	40	30	9
2	0.25	40	30	3
3	0.25	40	90	3
4	0.75	55	60	12
5	1.25	70	30	3
6	0.25	40	90	9
7	-0.25	55	60	6
8	1.25	40	90	3
9	1.25	70	30	9
10	0.75	85	60	6
11	0.75	55	60	6
12	0.75	55	60	6
13	0.25	70	30	9
14	1.25	70	90	3
15	1.25	70	90	9
16	0.75	25	60	6
17	1.25	40	90	9
18	1.75	55	60	6
19	0.25	70	30	3
20	0.75	55	60	0
21	0.75	55	60	6
22	1.25	40	30	9
23	0.25	70	90	3
24	0.75	55	120	6
25	0.75	55	60	6
26	0.75	55	60	6
27	1.25	40	30	3
28	0.75	55	60	6
29	0.75	55	0	6
30	0.25	70	90	9

3.3.4. Selection of Alcohols

The present research is dedicated to the self-sustainability of the nation in terms of fuel for the engines. For that, the direct injection CI engine is selected and the fuel selected for the engine is biodiesel prepared from jatropha oil. The primary issue in utilizing the JOME as fuel for engine is its viscosity which is higher compared to mineral diesel. Also, all diesel engines are designed by considering the properties of petroleum diesel engines. Therefore, it is very difficult to use 100% JOME as fuel in an unmodified diesel engine. So to complete the aim of the research the blending of JOME with non-petroleum fuel is necessary. As discussed earlier the properties of the number of non-petroleum fuels are analysed by studying the research articles and conclude that the alcohols are the best option among all. In alcohol, the higher alcohols having some great properties but yet to be explored completely. After evaluating the physicochemical properties of most of the alcohol it was analysed that the properties of n-butanol and n-octanol are very similar to petroleum diesel. So the n-butanol and n-octanol were selected for blending with JOME in different proportions in the present research.

The n-butanol and n-octanol used in the present research were procured from the standard chemical supplier of the national capital of India. The n-butanol and n-octanol used are having 98% pure grade. The properties of the n-butanol and n-octanol were tested in the CASRAE, DTU, Delhi, and compared to the results provided by the supplier. The value of tested properties is similar to the value of properties given by the supplier.

Table 3.6: Properties of alcohols[89], [90], [260]

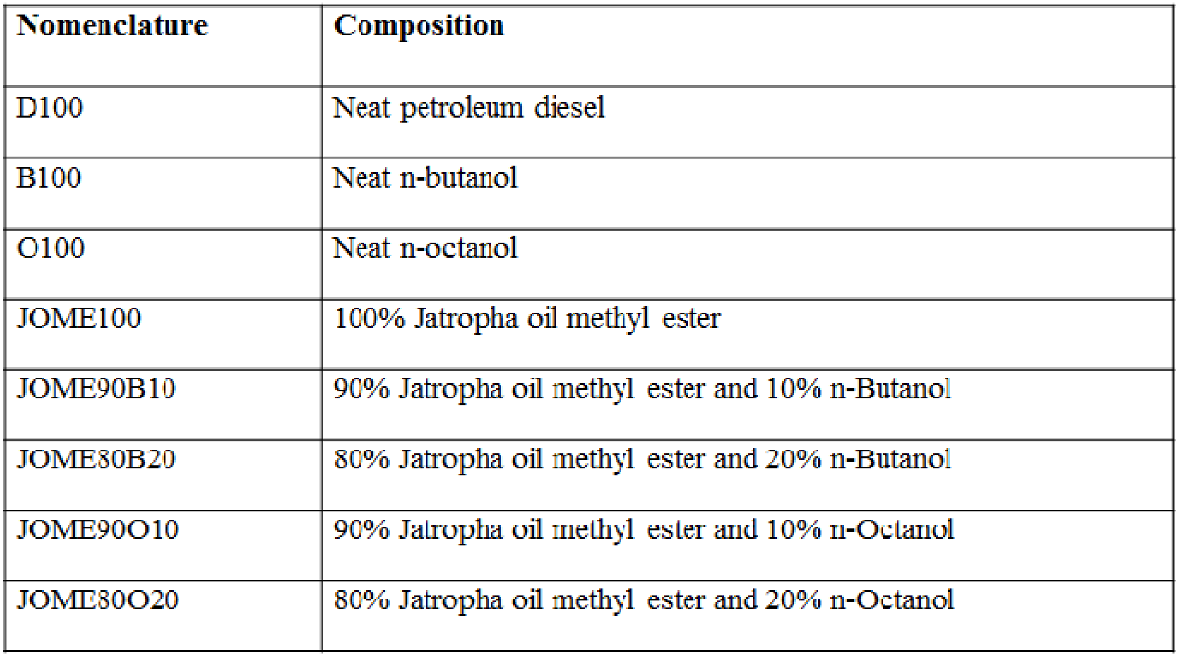


Properties	Diesel	Methanol	Ethanol	n-Butanol	n-Pentanol	n-Octanol
Molecular formula	C_XH_Y	CH_3-OH	C_2H_5-OH	C_4H_9-OH	C_5H_{11}-OH	C_8H_{17}-OH
Molecular weight	190-211.7	32.04	44.07	74.12	88.15	130.23
C (WT %)	86.13	37.48	52.14	64.82	68.13	73.72
H (WT %)	13.87	12.48	13.02	13.49	13.61	13.82
O (WT %)	0	49.93	34.73	21.59	18.15	12.29
Cetane number	45-52	,2-5	,8-11	17	18.2-20	39
self-ignition temperature (°C)	210-300	463	420	343-345	300	270
Density (15 °C)Kg/M3	835	791.3	789.4	809.7	814.8	827
Viscosity at 40 (°C) (mm/s2)	1.8-2.72	0.58-0.6	1.1-1.13	1.7-2.22	2.89	4.4-7.3
Lower heating value (MJ/Kg)	42.49	19.58	26.83	33.09	34.65	37.53
Latent heat of Vaporization(KJ/kg)	250-276	1162.64	918.42	581.4	308.05	408-545
Vapour pressure (mmHg)	0.4	127	55	7	6	0.08
CFPP b (°C)	-17	< -51	< -51	< -51	-40	-16
Boiling Point (°C)	150-360	65-64.7	78-78.3	117-117.5	137.9	195
Flash Point (°C)	52-96	11-12	17	29-37	49	81
Lubricity (µm corrected wear scar	315	1100	603	623		404

3.5 Tested Fuel Preparation

After procuring the n-butanol and n-octanol from the market, the various blends of JOME, n-butanol, and n-octanol were prepared by taking them in different proportions. The proportion of n-butanol and n-octanol is chosen so that, the properties of prepared blends are comparable with the diesel engine. However, it is very difficult to improve all the properties, therefore during blending the properties which play a vital role in combustion is focused. The blending was done at room temperature with a high speed hand blender so that a homogeneous mixture of both the components can be prepared. The blends are kept for 2 days in a closed container at room temperature to see the phase separation. No phase separation occurs in any of the blends for two days therefore these blends are selected for further work. The blends prepared for the present research are JOME90B10, JOME80B20, JOME90O10, and JOME80O20. The composition and nomenclature of all test fuels used are represented in table 3.7 also the prepared test blends are represented in plate 3.3.

Table 3.7: Composition and nomenclature of test fuels.



Nomenclature	**Composition**
D100	Neat petroleum diesel
B100	Neat n-butanol
O100	Neat n-octanol
JOME100	100% Jatropha oil methyl ester
JOME90B10	90% Jatropha oil methyl ester and 10% n-Butanol
JOME80B20	80% Jatropha oil methyl ester and 20% n-Butanol
JOME90O10	90% Jatropha oil methyl ester and 10% n-Octanol
JOME80O20	80% Jatropha oil methyl ester and 20% n-Octanol

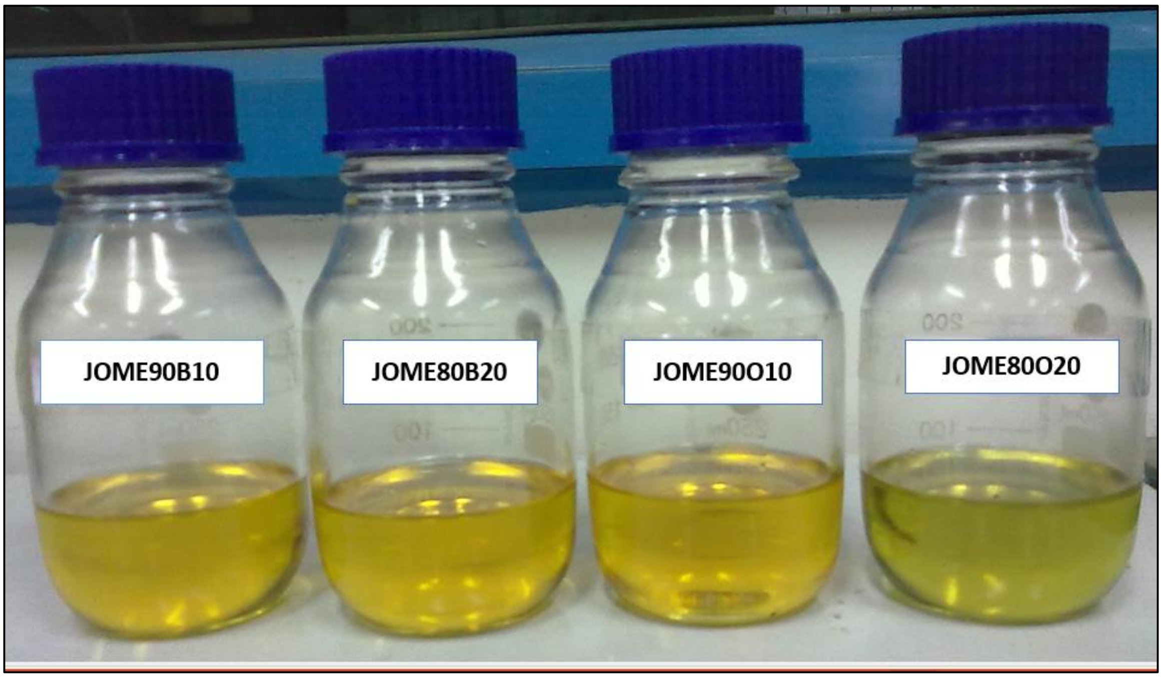
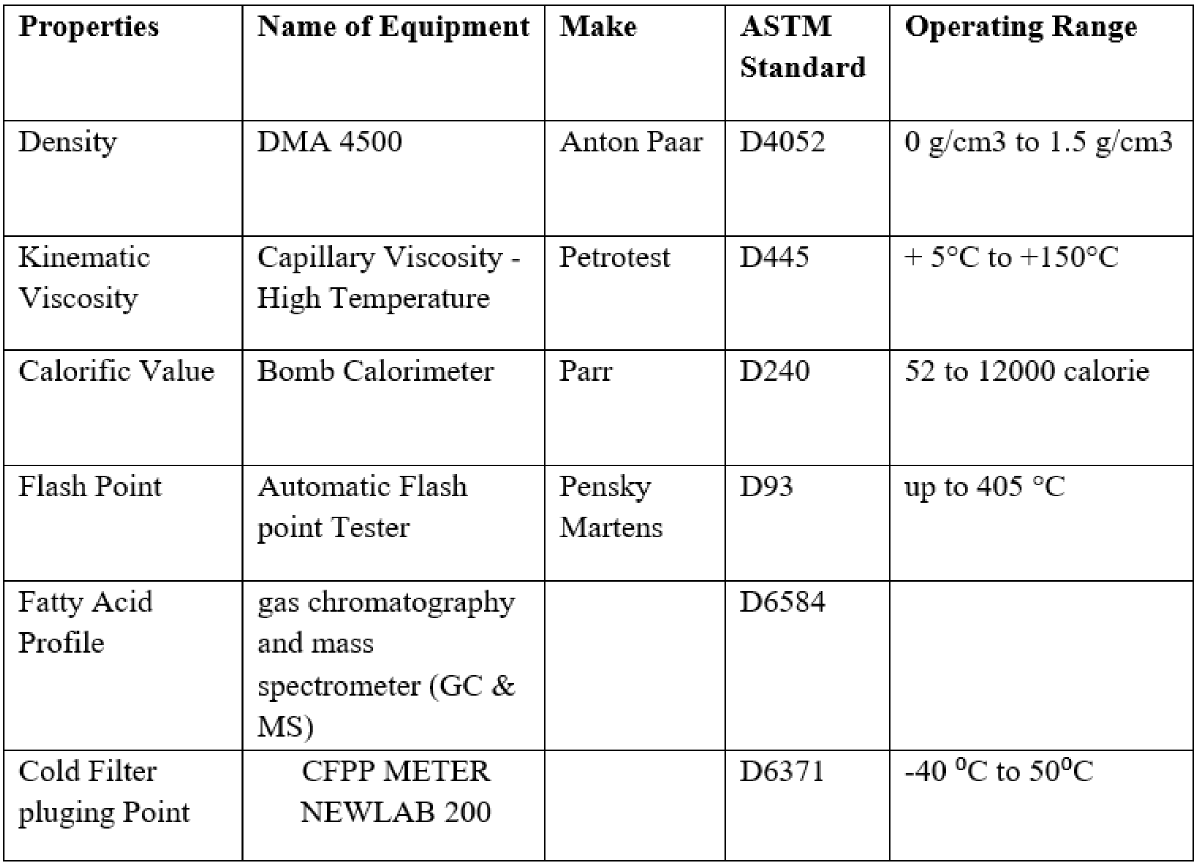


Plate 3.3: Sample of Blends

3.6 Properties of Tested Fuels

The physicochemical properties play an important role in analysing the results obtained from the diesel engine. Hence it becomes mandatory to measure all physicochemical properties of all fuels tested on the engine so that clear pictures can be analysed how they behave in the engine. In the present section, the methods of measuring all physicochemical properties of all tested fuel are discussed with their ASTM standards. The capillary column viscometer is for measuring kinematic viscosity of all test fuels and the standard followed during the measurement is ASTM D445 whereas the density is measured according to ASTM D4052 standard. The instrument used for measuring the density of all tested fuels is digital density meter. Further, the calorific value of all tested fuels is measured by oxygen bomb calorimeter which works on ASTM D240. The flash point of all tested fuel is also tested in CASRAE, DTU, Delhi along with all the above discussed properties. The flash point was measured with the ASTM D93 standard by using an automatic flash point tester. The cetane index was is also calculated according to ASTM D4737 by using four variable methods. Apart from that the fatty acid profile of all tested fuels is also measured as per standard ASTM D6584. The gas chromatography and mass spectrometer (GC & MS) instruments are used for measuring of fatty acid profile. This test was conducted in another lab. The list instruments used for measuring these properties are given in table 3.8 with their makers and operating range.

Table 3.8: Measuring equipment and their specifications.



Properties	**Name of Equipment**	**Make**	**ASTM Standard**	**Operating Range**
Density	DMA 4500	Anton Paar	D4052	0 g/cm3 to 1.5 g/cm3
Kinematic Viscosity	Capillary Viscosity - High Temperature	Petrotest	D445	+ 5°C to +150°C
Calorific Value	Bomb Calorimeter	Parr	D240	52 to 12000 calorie
Flash Point	Automatic Flash point Tester	Pensky Martens	D93	up to 405 °C
Fatty Acid Profile	gas chromatography and mass spectrometer (GC & MS)		D6584	
Cold Filter pluging Point	CFPP METER NEWLAB 200		D6371	-40 ^{0}C to 50^{0}C

3.6.1 Density

The Anto Paar DMA 4500 instrument is used to measure the density of all tested fuel in the present research which is shown in plate 3.4. Anto Paar DMA 4500 is working on oscillating technology in which the density of a liquid as well as gaseous fuel is calculated. In this method, the oscillation frequency is measured electronically. Before testing the instrument need to be clean so that it should free from all impurities. So before the operation instrument is clean with a clean cloth and before testing 10 ml of toluene is injected in the instrument to clean the test fuel pipeline. This process is repeated after each test fuel sample testing. During testing, the 10 ml sample of tested fuel is injected into the machine through an injecting port. The instrument measure the density of the tested sample and value is displayed on the screen. Four reading are taken for each sample and the average of all four values is taken as final density to minimize the error.

Plate 3.4: Density Meter

3.6.2 Kinematic viscosity

The plate shows the apparatus used for measuring kinematic viscosity of tested fuels. As discussed earlier that kinematic viscosity of fuel plays a very important role in combustion. The injection of fuel becomes very difficult through an unmodified fuel injector if its viscosity is very high. High viscous oil is difficult to atomize hence no proper combustion occurs for such fuels. Further, the high viscous oil form scum over the piston wall, piston head, and valves which might cause seizing. Hence low viscosity for tested fuel is desirable. In the present research kinematic viscometer is used to measure the viscosity of all tested fuels. The kinematic viscometer, measure the viscosity at 40°C. This instrument consists of one big container in which water is filled. The water is heated with the help of a water heater installed in that container only. The temperature of the water present in the tank is measured through thermocouple connected with the digital temperature indicator. The temperature controller is also connected to the temperature indicator which controls the power supply to the heater. The power supply to the water heater is given through the temperature controller. A capillary tube is placed inside the hot water in which the tested fuel is filled. Two marks are indicated on the capillary tube. The time taken by tested fuel from the upper mark to lower mark is measured with a stopwatch. That time is then used to determine the kinematic viscosity of the tested sample. Three reading for each tested fuel is taken and the average of these is taken as the final value. The viscometer utilized during the study is represented in plate 3.5.

The kinematic viscosity of different fuel blends can be calculated as:

$$\upsilon = c * t$$

Where,

υ= kinematic viscosity of sample;

c = constant for viscometer = 0.005675 mm^2/sec^2;

t = time taken by the fluid to flow through the capillary tube.

Plate 3.5: Viscometer

3.6.3. Flash point

The flash point also plays an important role in understanding the combustion characteristic of fuel. The flash point of fuel represents the lowest temperature on which the vapors of fuel are formed and these vapors mixed with air and ignite when it comes in contact with a hot surface. The temperature of the surface should higher than the auto ignition temperature of that fuel. The flash point of all tested fuels is measured with Pensky Martens automatic flash point apparatus which works on the ASTM D93 standard. The flash point apparatus used in current research is shown in plate 3.6.

Plate 3.6: Pensky Martens Automatic Flash Point apparatus

3.6.4. Calorific value

The calorific value is the amount of energy released by a unit mass of fuel during complete combustion. The calorific value is classified into two categories, (i) Lower calorific value and (ii) Higher calorific value. In most of the cases, the lower caloric value of the fuel is measured. The lower calorific value is defined as the total amount of energy liberated by the complete combustion of per unit mass or volume of fuel when side products are allowed to escape. The higher caloric value of the fuel is defined as the total amount of heat liberated during complete combustion of unit mass or volume of fuel and the by products are allowed to cool down to room temperature. The calorific value of all tested fuels is measured according to the ASTM D240 standard. For measuring the calorific value of all tested fuels, the isothermal bomb calorimeter is used which is present in the CASRAE, Delhi. One gram of tested fuel is taken in a small vessel which is kept in a cylinder covered with water. The combustion takes place at a constant volume that's why it is known as a bomb calorimeter. The sample of tested fuel is ignited with the help of an electric current wire. The bomb calorimeter used to measure the calorific value of all tested fuels in the centre is Parr 6100EF which is shown in plate 3.7.

Plate 3.7: Isothermal Bomb Calorimeter

3.6.5 Saponification value

The weight of triglyceride present in tested fuel can be termed as the saponification value or saponification number of the fuel. One standard method of measuring the saponification value of tested fuel is titration. In this method, one gram of oil is reacted with 10 ml of KOH. The reaction takes place either at room temperature or in the vapor environment. The reaction rate is faster in the vapor environment. To measure the amount of KOH consumed during neutralization, the solution is then treated with HCl. Two drops of the indicator are also put in the solution before titration. The amount of HCl consumed during titration of the solution is used to measure the amount of KOH present in the solution. This amount is then subtracted from the 10 ml to calculate the saponification value of the fuel. The reaction takes place during this process is given below:

Triglyceride + 3 KOH = Glycerol + 3 Fatty acid Salts of potassium

$$SV=560(\%FC)/M$$

SV-saponification value

M-molecular mass of each fatty acid component

FC-% of each fatty acid component

3.6.6 Distillation

The tested sample is consists of different components and all have different boiling points. So the distillation temperature help to understand the vaporization characteristics of the fuel in the combustion chamber. Also, distillation temperature used to determine the cetane index of the tested fuel which helps in understanding the combustion characteristics of the fuel. The distillation process conducted is as per standard ASTM D86 [261]. To measure the distillation temperature of tested fuels, the 100ml sample is put in a specially designed distillation flask which contains some sensors and thermocouples to continuous monitoring of temperature, pressure, and volume of the sample in the flask. The flask is then put on heater and heating rate is kept so that only 4-5 ml of oil evaporate per minute [262]. The vapors of sample oil are cooled with the help of the condenser maintaining a temperature of 10°C. The condensate is collected in a vessel and the volume of condensate is measured with the help of a digital volume sensor. The distillation temperature with different condensate volume is noted down. The temperature at 10% condensate volume, 50% condensate volume, and 90% condensate volume is measured for cetane index calculation.

3.6.7 Cetane index

Cetane index is a very imperative factor for understanding characteristics of all test fuels required for the better combustion process and this provides identical adjacent rapport to cetane number. The cetane number is measured cooperative fuel research (CFR) engine which is very rare to find in all research labs. Therefore to get an idea about the cetane number, the cetane index of the fuel is tested. The cetane index (CI) of all tested fuels is tested as per ASTM D4737 using four variable methods [263]. The four variables are density at 15°C, and the recovery of 10%, 50% and 90% of fuel through distillation temperature which is indicated with T_{10}, T_{50} and T_{90} respectively [262]. The formula used for finding the calculated cetane index (CCI) is:

$$\text{Cetane index} = 45.2 + 0.0892T_{10N} + (0.131+0.901B)\ T_{50N} + (0.0523-0.420B)\ T_{90N} + 0.00049[(T_{10N})^2-(T_{90N})^2] + 107B + 60B^2$$

Where:

D = Density at 15°C in g/mL

$DN = D-0.85$

$B = e^{-3.5DN} - 1$

$T_{10N} = T_{10} - 215$

$T_{50N} = T_{50} - 260$

$T_{90N} = T_{90} - 310$

3.6.8. Iodine value

Iodine value (IV) is the amount of I_2 in mg that is consumed by 100 g of substrates in a chemical reaction. It usually measures the addition of double bonds in fatty acids that are related to unsaturation. This property influences the oxidation stability and polymerization of glycerides, leading to the formation of deposits in diesel engines injectors. Iodine value is directly correlated to biodiesel viscosity, cetane number, and cold flow characteristics.

$$IV= (254*DB*\%FC)/M$$

DB-number of double bonds

M-molecular mass of each fatty acid component

FC-% of each fatty acid component

3.6.9. Cold filter plugging point

The lowest temperature at which a fuel does not flow through the filter or required more than 60 seconds for 20 ml to pass through is termed as cold filter plugging point (CFPP). One of the biggest problems with biodiesel is its poor flow property at a lower temperature. The CFPP of the test fuels is measured through CFPP meter which is shown in plate 3.8. To measure the CFPP temperature, the test fuel is cooled under a vacuum of 200mm water gauge, and the temperature is reduced with a fraction of one degree Celsius. In this condition test fuel is passed through a very fine mesh filter to aspiration pipette. Once the temperature of the test fuel reaches below is the cold point, the wax crystals are formed. With the further decrease in temperature, the wax crystal goes thicker and thicker. An increase in the size of the wax crystal increases the density of fuel and slow down the flow speed. These crystals deposit over the fuel filter and lead to the chocking of the fuel filter. When the flow of 20ml of test fuel took more than 60 seconds, the instrument record the temperature which is represented as CFPP temperature.

The lower CFPP temperature is preferable for the fuel as it can be used at very low temperatures without any hurdles. The biodiesel consists of saturated fatty acids and unsaturated fatty acid compounds. The saturated fatty acid has a higher melting point as compared to an unsaturated fatty acid. This is the main reason that most of the biodiesel has a higher CFPP temperature compared to mineral diesel.

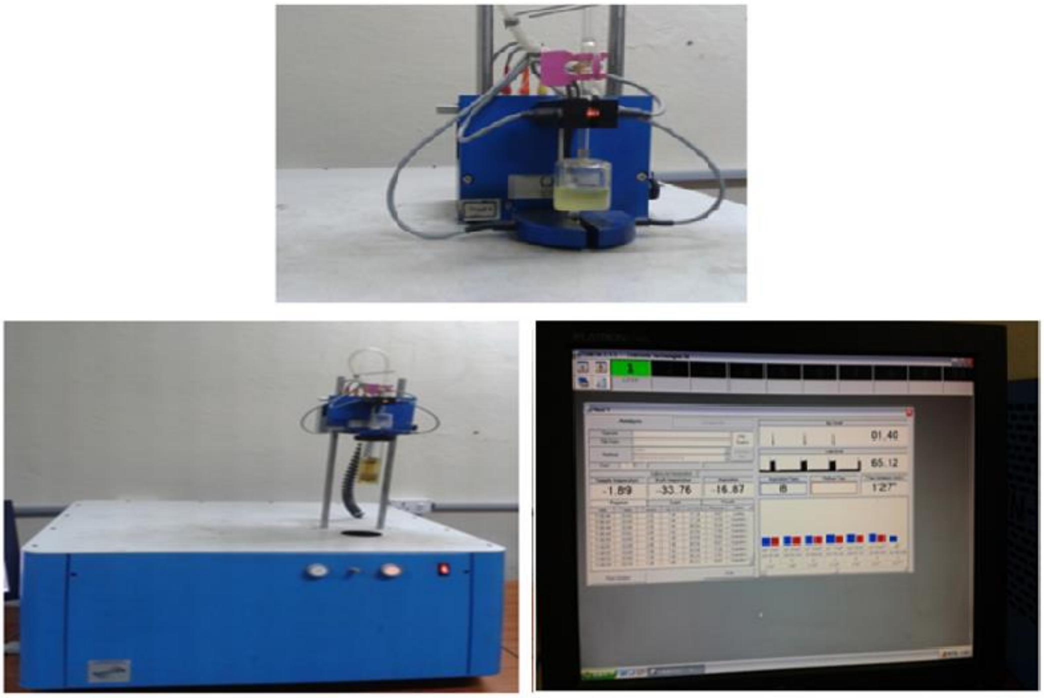


Plate 3.8: CFPP Meter

3.7 Fatty Acid Composition

The biodiesel prepared from jatropha oil contains the number of the fatty acid component which behaves individually. For determining the fatty acid composition of JOME, the JOME is tested on equipment GC-MS which is stands for gas chromatography-mass spectroscopy. This instrument is used to determine the chemical composition of complex structured chemicals. The GM-MS instrument contains a narrow tube also known as a column, this column has very long in the form of helical spring. The temperature of the column gradually increasing with the length of the column. The instrument is started and inert gas like helium and nitrogen is passed through the column before the experiment so that any unwanted gas or impurities present in the column comes out with the gases. After that, a small quantity of oil samples is poured in the column which moves in the column with very slow speed. As described earlier that the temperature of the column is increasing with length. Hence, the sample oil starts heating and the component which has a lower boiling point gets evaporated and starts moving at a faster speed and comes out to the column from another end. Similarly, the other component also converted into vapor at different temperatures and comes out from the column. One electronic detector is placed on the other end of the column. Therefore, the chemicals that come out from the column get detected electronically. Hence, the prime intension of the static column is to separate the different chemical components of the tested fuel. The mass spectroscopy converts ions into mass and the exact composition of the tested fuel can be determined. The GC-MS used in the present study is shown in plate 3.9.

Plate 3.9: GC-MS Apparatus

3.8. Engine Test Rig:

The engine utilized during the current analysis was Kirloskar stationary, single cylinder, and four stroke diesel engine. This engine is already introduced at the beginning of this chapter. This light duty water cooled mechanically governed diesel engine was selected due to its high popularity in India. The engine was fitted over a foundation made with concrete to reduce the vibration effect so that minimum variation in data occurs. The engine used in the current research was unmodified except for the introduction of two fuel tanks. One fuel tank is dedicatedly given for petroleum diesel only however the second fuel tank is used for other tested fuels. The tank is cleaned perfectly before using different test fuel with the help of methanol. The supply of both the fuel to the engine is through the common burette. The fuel burette distributes and controls the amount of fuel flow rate to the engine. The supply of fuel to the engine is controlled by the governor to maintain fixed engine speed for all loading conditions. The pressure of fuel injected is controlled with fuel injectors and fuel pumps. The fuel pump is governed with a shaft which is coupled with the prime mover shaft. The intake and exhaust valve are mechanically controlled with the help of cams and followers. The cams of the intake valve, exhaust valve, and fuel pump are connected to the same shaft. The speed of this shaft is half the speed of prime mover shaft. The k-type thermocouple, to measure the exhaust gas temperature, was installed on the exhaust manifold.

Air to the current research engine was supplied through the airbox which is connected with the intake manifold. The airbox is installed because of two measure reasons: one, for air mass flow rate measurement and second to supply air to the engine at a constant temperature. For that one heater was also installed in the airbox which controls the temperature of the intake air. The U-tube manometer was utilized for measuring air flow rate which is installed at the airbox however temperature of intake air is checked through a k-type thermocouple which is installed at the intake manifold. One magnetic pickup speed sensor was installed on the prime mover shaft of a research engine that measures the speed of the research engine.

The combustion characteristics’ for all test fuels while use in the current research engine were also taken care of in the present research for that the inside cylinder pressure of the research engine for all test fuels was analysed at all loads. Therefore, one kebeler piezo pressure sensor was installed overhead of the research engine which has a maximum resolution of 1°CA. The pressure measuring unit consist of the pressure transducer and data amplifier which is connected to a personal computer and the data is read by the enginesoft software installed on the personal computer. To notice the variation in the performance of the engine on various loading conditions one eddy current dynamometer was coupled with prime mover shaft of the engine. It consists of a stator which is fitted with a number of electromagnets & rotor disc and this assembly is coupled with the prime mover. The eddy current is produced in the stator while rotation of rotor due to the setup of magnetic flux bypassing of field current in electromagnets. The eddy current opposes the rotor motion which results in loading on the prime mover. The continuous resistance to the motion generates heat which is removed continuously by supplying cold water to the dynamometer. The pollutant emitted by a diesel engine is the foremost concern. Hence, the exhaust gas was also analysed in the present research. The major pollutants like CO, HC, NO_X and smoke opacity, etc. were measured in the present research. The exhaust emissions of the research engine were measured by AVL 4000 Light Di-Gas analyser. One the other hand, another major emission parameter i.e. smoke opacity of the research engine was measured through AVL 437 smoke meter. The detailed procedure of measurement is explained further in this chapter.

Most of the indicators and controlling devices of the engine were fixed on the control panel which is installed near to the engine. Load varying switch is installed on the control panel by which a load of eddy current dynamometer can be increased. The control panel also consists of fuel burette and fuel switching valve by which the fuel flow rate is a measure also fuel can be switch over from petroleum diesel to other tested fuel or vice versa. The control panel also consists of a charge amplifier that is further connected to the personal computer. The speed indicator is also put on the control panel and all this data through the data acquisition system is sent to a personal computer.

Finally, the test rig of the present research was consist of lightweight water cooled CI engine, air filter, control panel, loading & measuring unit, fuel filters, fuel supply and measuring unit, fuel switching system, temperature measuring and controlling system, speed measuring and controlling system, exhaust gas emissions and the smoke analysing unit, in-cylinder pressure measuring and analysing system, digital data acquisition system, and control panel and a personal computer with engine soft software and other data analysing software. The test rig used in the present research is shown in figure 3.2 &plate 3.10 represents the schematic diagram of the setup used in current research. Eddy's current dynamometer is shown in plate 3.11. Table 3.9 represents the specifications of the dynamometer utilized during the current research.

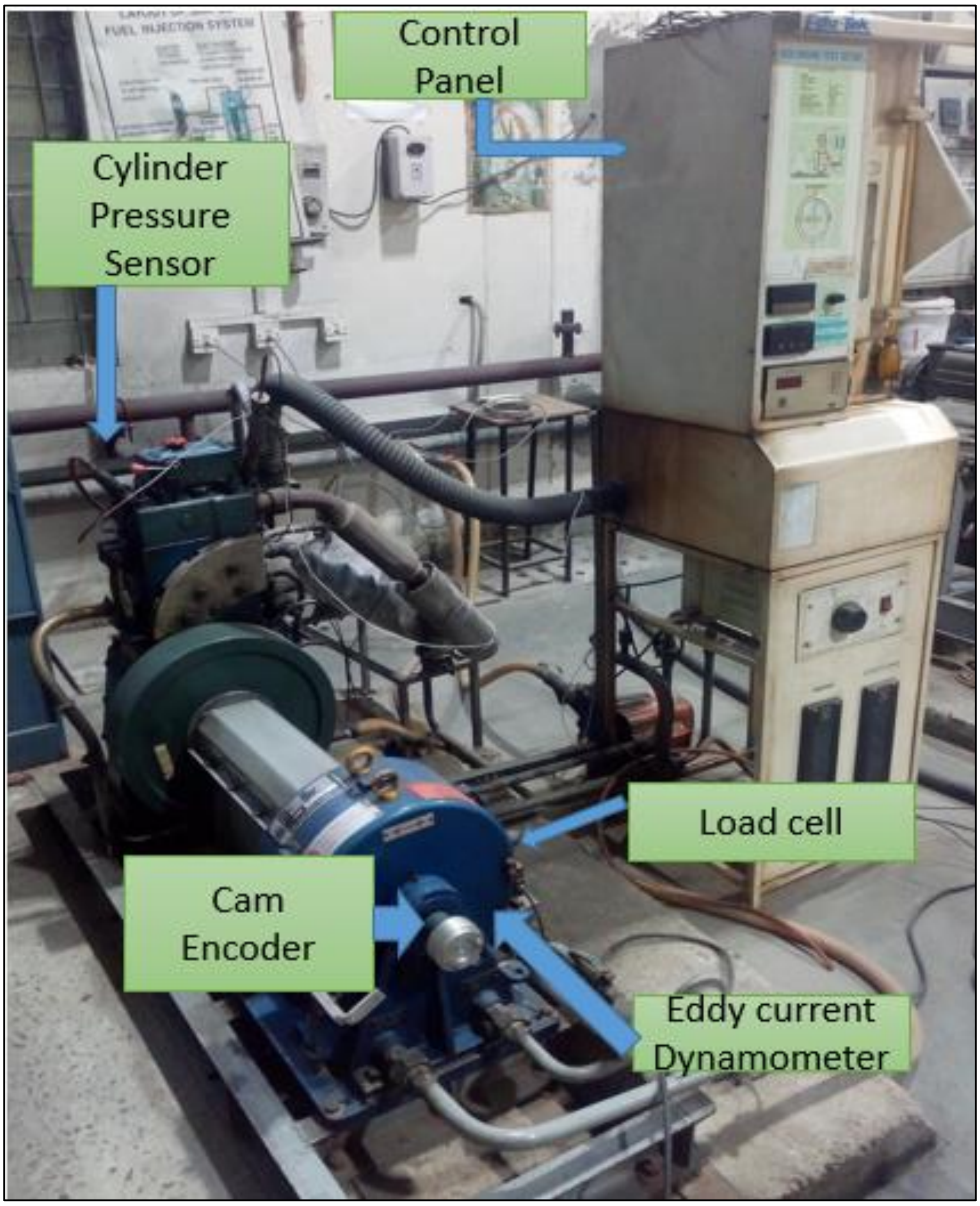


Plate 3.10: Experimental Test Rig

The test rig is shown in plate 3.10 and the schematic diagram in figure 3.3. The specification of all other measuring instruments is presented in table 3.10.

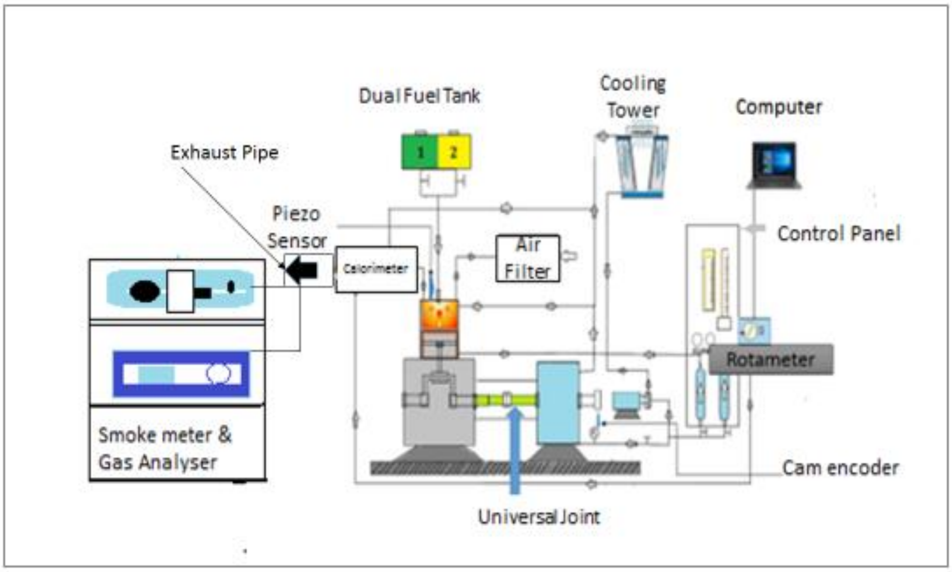


Figure 3.3: Test rig.

Plate 3.11: Eddy Current Dynamometer

Table 3.9: Dynamometer specification.

S. No.	Dynamometer Specification	
1.	Make	Technomech,TMEC-10
2.	RPM	1500-5000
3.	Dynamometer Arm length	185 mm
4.	Dynamometer type	Eddy Current
5.	Load cell	Strain gauge type
6.	Load	7.5 Kw

Table 3.10: Specifications of all the instruments & sensors.

Sl. No.	Instrument and sensors	
1	Engine load	Strain gauge type load cell
2	Speed	Magnetic pickup type
3	Time	Stop watch
4	Exhaust Temperature	K-type thermocouple
5	Crank angle sensor	Optical
6	Pressure	Piezo sensor
7	Fuel consumption	Differential pressure
8	Air consumption	Air box with orifice/Air transducer
9	Smoke meter	AVL 437
10	Emission analyser	AVL Di-gas 444

3.9. Engine Observed Parameters

The detailed procedure of measuring of observed parameters during the present research is explained in the current section. The observed parameters are very necessary to analyse the engine performance and these are selected very carefully. The list of observed parameters in the present research is given below:

- Engine speed.
- Engine load.
- Fuel consumption rate
- Airflow rate.
- In-cylinder pressure.
- Exhaust temperature.
- Exhaust emissions.
- Smoke opacity.

3.9.1 Engine speed

The engine used in the current research was stationary, a constant speed engine. But, the speed of the research engine varies with respect to the load which affects the calculation of engine performance. Hence it becomes important to notice the fluctuation of speed with respect to the load and the exact value is kept for calculation. The speed of the engine is measured by installing a magnetic pickup speed meter on the flywheel of the engine. This system contains one permanent magnet, yoke, and coil. The tooth is mounted on the flywheel where the sensor is fixed closer to the tooth to neglect the chance of error. The speed of the tooth is equal to the speed of flywheel which is directly coupled with the prime mover shaft. The passing of the tooth over the sensor generates pulses which are measured by the speedometer. The data obtained from speedometer is fed into where it is synchronized with the pressure data so the accurate pressure rise rate can be monitored. The calculation for the speed of the engine is done using the formula given:

$$\text{Engine speed} = \frac{Number\ of\ pulses\ per\ minute}{Number\ of\ teeth\ on\ the\ shaft}$$

In the current setup, only one tooth is placed on the flywheel. Hence the engine speed is equal to the number of pulses generated per minute.

3.9.2 Engine load

The rated power of the engine used in the current research was5.2 kW. However, the speed of the engine decreases slightly but it remains close to 1500 rpm. The load on the research engine was applied through the eddy current dynamometer. The engine trial done on 0%, 20%, 40%, 60%, 80% and 100% loading condition. The combustion, performance & exhaust emissions of the research engine for all tested fuels were analysed on all these loading conditions.

3.9.3 Measurement of fuel flow rate

The calculation of the performance of the research engine required fuel flow rate data along with loading data. As discussed earlier, one burette was installed on the control panel to measure the fuel flow rate to the research engine. The fuel supply to the engine is done in such a way that the fuel can be supplied continuously to research engines from various fuels tank as well as burette. The fuel in the burette is supplied from the fuel tank. The fuel supply to the research engine is cut from the fuel tank to measure of fuel flow rate. The stopwatch was utilized to measure time for a fixed volume of fuel supplied is measured. This process is repeated 5 times for one tested fuel at a particular load. The average of all the times taken to consume the fuel of fixed volume was calculated and keep it as a final reading. Now the mass flow rate of fuel is equal to the product of fixed volume consumed and the density of fuel divided by the average time of five reading at a particular load. The formula is given as follows:

$$\text{Rate of fuel consumed} = \frac{Fixed\ volume\ of\ fuel\ X\ Density\ of\ fuel}{Average\ time\ to\ consume\ fixed\ volume\ of\ fuel}$$

In the present research, the volume of the fuel was fixed at 20 ml. The energy flow rate was also calculated for the comparative purpose of different tested fuels. As the calorific value of all fuels is different hence it becomes difficult to compare them with respect to mass flow rate. The energy flow rate is the product of the mass flow rate of fuel and its calorific value. The fuel flow is also measured electronically by differential pressure (DP) oil flow transmitter which works on the principle of differential pressure diaphragm, shown in plate 3.12. The data obtained from the transmitter can be validated with the help of flow rate measured by burette and stopwatch, installed on the control panel

Both readings were compared for accuracy. The analytical formula used for the rate of energy consumption is given as:

Rate of energy flow = fuel mass flow rate x calorific value.

3.9.4. Measurement of airflow

The airflow was measured through the airbox with an orifice which is connected with the intake manifold. The U-tube manometer is utilized for airflow rate which is installed at the airbox. The calculation for the airflow rate is done by using the following equation.

The data collected by the airflow transmitter is sent to the data acquisition system and the flow of air is determined. The air quantity measured from the sensor can be validated with the help of the flow rate analytically calculated with the help of an airbox with an orifice in the control panel. The airflow transmitter is shown in figure 3.13 which is installed inside of control panel.

$$\text{Airflow rate } (\dot{m}_a) = C_d * A * \sqrt{(2gh_w\rho_{w/}\rho_a)}$$

Where:

C_d = Co-efficient of discharge of venturi (0.9 in the present case)

A = Orifice area

g = Acceleration due to gravity

h_w = Height of water column

ρ_w/ρ_a = Density of water/air

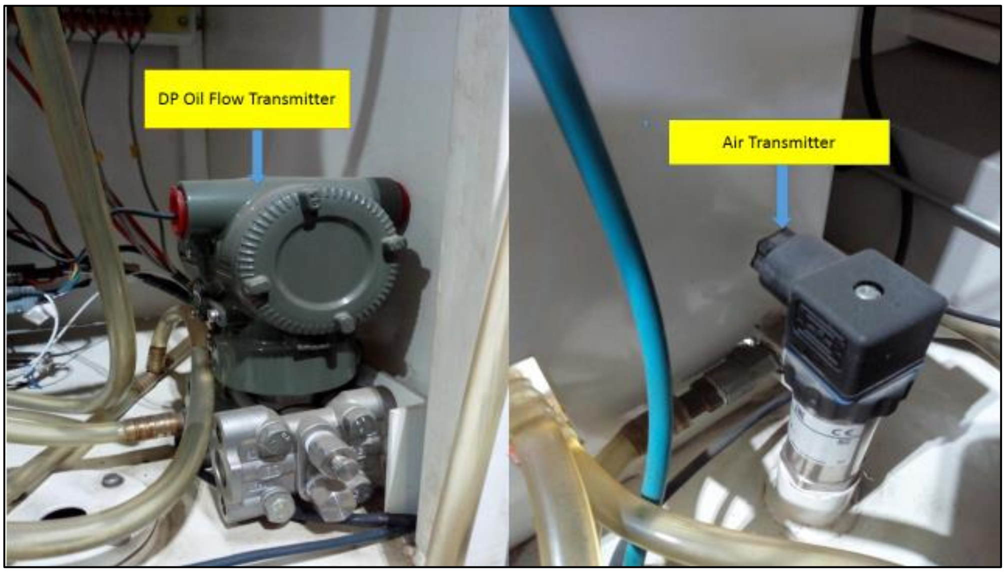


Plate 3.12: Oil and air Flow Transmitter

3.9.5. Inside cylinder pressure measurement

The inside cylinder pressure is a very significant consideration to scrutinize the combustion characteristics of test fuels in the research engine. Hence, it becomes necessary to measure the change of inside cylinder pressure w.r.t. per crank angle rotation for the research engine. As introduced earlier, the inside cylinder pressure was measured by installing one piezoelectric transducer over the research engine head. The signal from the piezo sensor is sent to the charge amplifier from where it amplifies to the data acquisition channel and then, the software converts the signals into digital data. Also, the data collected from speedometer is transfer to the data channel, and both inside pressure and engine speed are synchronized through software. The enginesoft database software was used to monitor and storing of inside cylinder pressure w.r.t. per angle rotation of crank rotation. To minimize the error more than 150 cycles were considered to analyse the inside cylinder pressure deed w.r.t. per angle crank rotation.

3.9.6 Measurement of exhaust temperature

The exhaust temperature is an important parameter to analyse combustion, performance, and exhaust emission results of the research engine. The higher temperature of exhaust gas shows sudden combustion and responsible for higher NO_X emissions as well. One K-type thermocouple was installed at the end of the exhaust pipe i.e. outside of calorimeter. The thermocouple is very accurate and calibrated from time to time. The temperature measured by thermocouple can be observed from the temperature indicator installed on the control panel as well as from the enginesoft database software.

3.9.7 Measurement of exhaust emissions

The level of air pollution is increasing day by day. The exhaust emissions released from the automobiles and the stationary engine is one of the biggest factors of this increasing air pollution. Hence, it becomes very important to control the exhaust emissions of the research engine. Therefore, AVL-4000 di-gas analyser is chosen for exhaust gas measurement (like NO_X, HC, and CO) where AVL-437 smoke meter was selected for measuring smoke opacity of the research engine. AVL-4000 di-gas analyser contains various sensors for all major exhaust emissions. The exhaust emissions pass through all the sensors and these sensors take their time to analyse the data and display that on a digital meter. The AVL-437 smoke meter works on a light projection method. The exhaust gas enters into the smoke meter and a beam of light is projected over the exhaust gas. A part of the beam is scattered by the pollutant present in exhaust gas also some part of the light beam is absorbed by these pollutants. The remaining portion of the light is falling on the absorber place opposite to beam source and this fall in light generates a photoelectric current. The smoke opacity of exhaust can be measured by measuring photoelectric current. Both instruments have their warm-up time. Therefore, both the instruments warm-up first and then utilized. The prob of the instruments was put in the exhaust manifold one by one and give enough time for stabilized first and take reading afterward. Three reading are taken for one loading condition of all tested fuel to minimize the error. The AVL-4000 and AVL-437 are shown in plate 3.13 while the specifications of AVL-4000 and AVL-437 is an exhibit in table 3.11 and table 3.12 respectively.

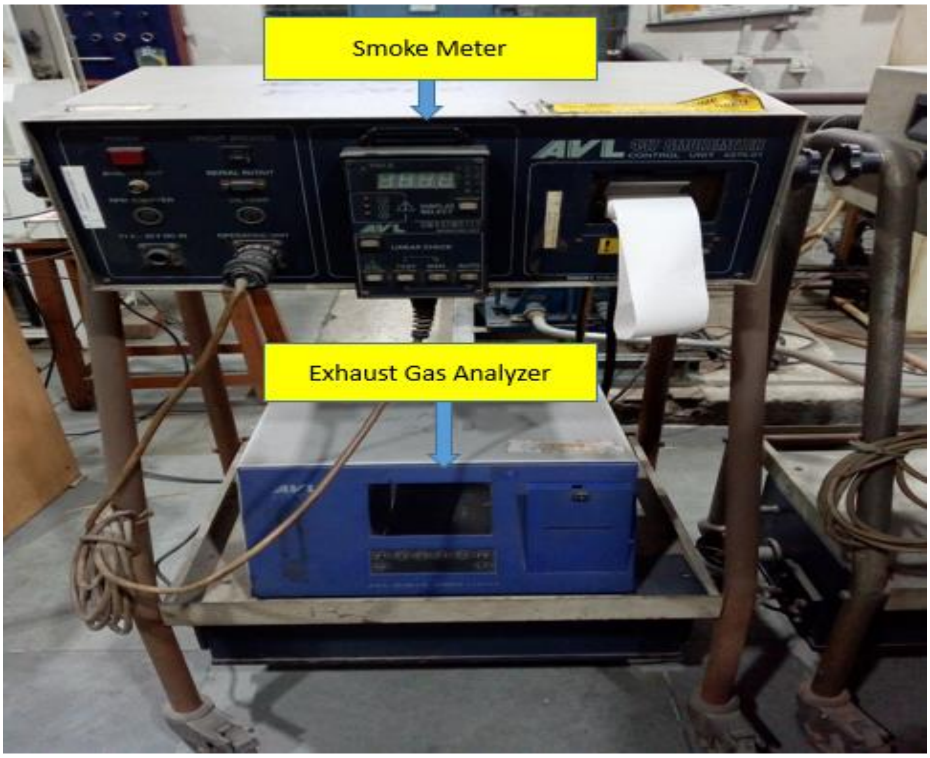


Plate 3.13: Smoke Meter and Gas Analyser

Table 3.11: Technical Specifications of AVL Di-Gas Analyser

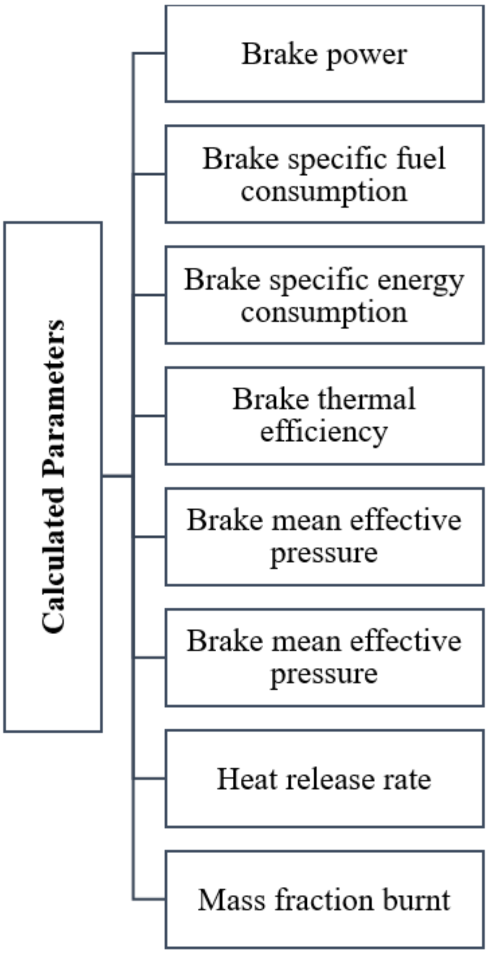
Measurement principle:	CO, HC	Infrared Measurement
	O_2	Electromechanical
	NO(option)	Electromechanical
Operating Temperature	+5 to +45 °C	keeping measurement accuracy
	+1 to +50 °C	Ready for measurement
	+5 to +35 °C	With integral NO sensor (peaks of :+40)
Storage temperature	-20 to +60°C	
	-20 to +50°C	With integrated O2 sensor
	-10 to. +45°C	With integrated NO sensor
	0 to +50°C	With water in filter and / or pump
Operating voltage		230VAC ±10%/110VAC ±10%
Power Consumption		150 VA
Dimensions (WxHxD)		432 x 230 x 470 mm

Table 3.12: Specifications of smoke meter

Accuracy and Reproducibility	±1% full scale reading
Measurement Chamber	Effective length 0.430 m± 0.005
Heating Time	220 V in approx20 min
Light Source	Halogen bulb 12V/5W
Colour Temperature	3000K ± 150K
Detector	Selenium photocell diameter 45mm. Max Sensitivity in light, In frequency range 550 to 570nm. Below 430 nm to 680 nm sensitivity is less than 4% related to the maximum sensitivity.
Maximum smoke temperature: At entrance	250 °C

3.10 Engine's Calculated Parameters

Some parameters cannot measure directly with the help of some instruments and devices but these are important for analysing the engine performance completely. Hence, once the data of all the measured parameters were obtained, the next step is to calculate some other important parameters with the help of data obtained from measured parameters. These parameters are known as calculated parameters. These parameters are calculated with the help of thermodynamic relationships, equations, and principles. The calculation is done manually as well as with the help of a computer. The equations, relationships, and principles used during calculation are discussed in this section. The engine's calculated parameters discussed in this section are:



3.10.1. Brake power

The power available on prime mover shaft is generally known with brake power. This term refers to engine load. The brake power was calculated with the help of a dynamometer. In the present research, an eddy current dynamometer was used. The load applied in the Eddy current dynamometer is in the form of electric current i.e. voltage and current through load controller. The formula used for the calculation of brake power in the present research is as follows:

$$BP\ (KW) = \frac{2\pi NT}{60\mathrm{X}1000}$$

T = W x 9.81 x R

T = Torque

W = Load (kg)

R = Arm length of dynamometer (meter)

3.10.2 Brake mean effective pressure

The calculation of power theoretically is simplified by an important parameter known as brake mean effective pressure (BMEP) which is calculated in this section. The main motive of the calculation of BMEP is to bring all the engines on one platform so that it becomes easy to compare all the engines. The rated power of the different types of engines is different however the BMEP almost remains constant for all engines. Hence, BMEP makes easy in comparing the performance of different size and capacity engines. The formula used for calculating BMEP in the present research is given below:

$$\text{BMEP} = \frac{2\ X\ 60\ X\ BP\ (kW)}{L\ X\ A\ X\ N\ X\ 101.325}\ \text{bar}$$

Where:

"L" is the stroke length

"A" is Cross-sectional area of piston ($\pi D^2/4$)

"N/60" is the rotational speed of the engine in revolution per second

101.325 kPa is Atmospheric Pressure

2 is for four stroke engine

"BP" represents Brake power of the engine

3.10.3. Brake specific fuel consumption

The rate of fuel consumed per unit of brake power is explicitly recognized as brake specific fuel consumption (BSFC). For the present research, it represents the mass of fuel required for per kW of brake power. It explicated the performance of the engine, less is the amount of fuel consumption, better is the engine performance. The formula used for calculating the BSFC is given as:

$$\text{BSFC} = \frac{mass\ flow\ rate\ of\ fuel\ X\ 3600}{BP\ (kW)}\ \text{g/kW-hr}$$

3.10.4. Brake specific energy consumption

In the present research different fuels are used which has different calorific value. Therefore to bring all test fuel on the same platform for comparison, brake specific energy consumption (BSEC) was measured as brake specific fuel consumption does not provide symmetry to the analysis. For comparison, BSFC of different test fuels is multiplied with their calorific value. Therefore, BSEC is the quotient of the rate of energy delivered to engine and brake power generated by the engine. The formula used to calculate BSEC in the present research is as follows:

$$\text{BSEC} = \frac{m\ X\ CV\ X\ 3600}{BP\ (kW)}\ \text{MJ/kW-hr}$$

Where:

“m" is fuel flow rate (kg/s).
“CV” stands for calorific value and measured in MJ

Also BSEC = BSFC * CV

3.10.5. Brake thermal efficiency

The effectiveness of test fuels in the research engine can be analysed with a very important factor publically known as brake thermal efficiency (BTE). The BTE is inversely proportional to the BSEC and also calculated by dividing the brake power of the engine with energy consumed for producing that brake power. In simple words, the BTE is reciprocal of BSEC. The formula used for calculation of BTE is:

$$\text{BTE} = \frac{Brake\ Power\ (kW)}{m\ X\ CV}$$

3.10.6. Calculation of heat release rate

The diesel engine is one type of “heat engine in which the chemical energy of the fuel is converted into heat energy” and that heat energy is used for further work [264]. Therefore, heat energy calculation becomes very important to understand the efficiency of the research engine. So measuring the heat release rate (HRR) in this consequence becomes very vital. The HRR per cycle in the present study also provides better clarity for empathetic of combustion and performance of the research engine. The speed of the engine is very high which makes it very difficult to measure the HRR directly while the engine is running. Therefore, some observed parameters are considered for the calculation of HRR of the research engine with the help of the number of formulas and relationships that are used for the calculation. Several methods are already described by various researchers to calculate the different parameters such as HRR, mass fraction burnt, and pressure rise rate. A few methods are very famous and used in the number of studies. In the present research, the heat release rate is calculated by the method explained by Rakopoulos [265]. The heat release rate for spark ignition engines and compressed ignition engines are very much different due to the nature of the mixture of air fuel [266]. In the SI engine, the homogeneous mixture of air & fuel combusts during power stroke on the other hand in CI engines the heterogeneous mixture of fuel & air combust. Further, it is very difficult to analyse the combustion for a heterogeneous mixture so for calculation purposes the combustion is assumed to be as homogeneous. This study is also known as a zero-dimensional model and suggested by Sorenson [266]. While calculating the heat balance in the combustion chamber the heat loss through piston rings is neglected [267]. The HRR in the combustion chamber is calculated through inside cylinder pressure measured per angle crank rotation. Therefore the heat balanced inside the combustion chamber can be written as:

$$\frac{dQ}{d\theta}-\frac{dQw}{d\theta} = \frac{d(\mathrm{mu})}{d\theta}+ \mathrm{P}\,\frac{dV}{d\theta} = \mathrm{mC_v}\,\frac{dT}{d\theta} + \mathrm{P}\,\frac{dV}{d\theta}$$

Q is heat release and Q_W is heat loss through the wall, θ is the crank angle. Therefore, dQ/dθ is net HRR of the inside combustion chamber and dQw/dθ is the rate of heat loss through the wall of the cylinder. The mass of the homogeneous mixture of air and gas is represented by m and assumed that it behaves like an ideal gas, u is the internal energy of mixture. Other terms like P, Cv, T, and V represents their basic notification and the represents in SI units only.

After differentiating the universal gas equation w.r.t. crank angle it comes:

$$\mathrm{P}\,\frac{dV}{d\theta} + \mathrm{V}\,\frac{dP}{d\theta} = \mathrm{mR}\,\frac{dT}{d\theta}$$

Substituting these value in the above equation we got

$$\frac{dQ}{d\theta} = \mathrm{P}\,\frac{Cp}{R}\frac{dV}{d\theta}+\mathrm{V}.\frac{Cv}{R}\frac{dP}{d\theta}+\mathrm{mT}\,\frac{dCv}{d\theta} + \frac{dQw}{d\theta}$$

The simplify representation of above equation is as:

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

The heat release that occurs in CI engines is typically taken between the start of injection and the opening of the exhaust valve. However, the combustion starts after a delay period only but that period is not considered. The fuel was injected at 23° before top dead center (bTDC) which is fixed as per the engine design and exhaust valve open at 35.5° before bottom dead centre (bBDC). Therefore the crank angle taken for heat release is considered between 320° to 504.5° for the present study. The crank angle used in trigonometric function needs to change in radian. Therefore, the crank angle is converted into radian first. The equation used to convert crank angle into radian is given as,

$$\theta_{rad} = \frac{\pi(\theta-360+\text{Phase})}{180}$$

Here, θ_{rad} represents the trigonometric function of the crank angle in radian and Phase represents the phase shift angle in the degree of crank angle rotation.

The gas volume needs to calculate for all crank angles. Therefore to calculate volume in the cylinder the piston displacement is used. The equations used to calculate the gas volume in the cylinder is:

$$S= R\left[\{1-\cos\theta_{rad}\} + \frac{L}{R}\left\{1-\left(\sqrt{1-\frac{\sin\theta rad}{L/R}}\right)^2\right\}\right]$$

$$V = V_{cl} + S\,A_p$$

Where "S" represents the piston displacement from top dead centre (TDC) (m), "L" is the length of the connecting rod and "R" represents the crankpin radius all value is taken in meter only. Also "A_p" represents the top area of the piston (m^2), "V_{cl}" is clearance volume of the engine (m^3)."V" represents gas volume (m^3)

Also, the wall area is calculated as:

$$A_{wall} = 2A_p + \pi\, DS$$

The area of the piston cup is neglected in the present study while calculating the heat loss. This neglecting might change the results of heat release but the effect is very small.

The data obtained through the inside pressure rate (dP/dθ) is utilized to establish a relation for heat release. The slop of dP/dθ curve at any point is given by the equation:

$$\frac{dPj}{d\theta} = \frac{n\Sigma(Pi\theta i) - \Sigma Pi\ \Sigma\theta i}{n\Sigma(\theta i)2 - (\Sigma\theta i)2}$$

Where n is an odd number and each summation is from [j – (n – 1)/2] to [j + (n – 1)/2].

The inside pressure is measured w.r.t. crank angle rotation keeping the equal diversions of angle which is measured through shaft encoder and synchronized with inside pressure data [9]. The equal spacing of Δθ is selected by the software along the θ axis. The large value for n is taken during the analysis so that the slop of the curve comes near to the actual pattern followed inside the cylinder. But the higher value of "n" makes the analysis bit complex. In the current research, Δθ = 1° is chosen for the value of n = 7 was found to fit the below equation over 4^o of the pressure trace. The pressure curve is smoothening through the equation give as:

$$P_{j+1} = P_j + \frac{dPj}{d\theta}\Delta\theta$$

The dV/dθ is calculated for any instant by the following relation:

$$\frac{dVj}{d\theta} = V_j - V_{j-1}$$

As combustion starts inside the cylinder, the temperature change takes place very frequently. This frequent change in temperature leads to variation in the properties of the air fuel mixture. The value of γ is calculated through the ideal gas relationship by considering the average inside the combustion chamber temperature as stated below:

$$T_j = \frac{PjVj}{MRg}$$

Where: T_j = bulk gas temperature at point j (°K); R_g = idea gas constant = 8.314/29 = 0.287; M = mass of charge, g = (1 + AF) mf; AF = air/fuel ratio of engine; m_f= mass of fuel injected into each engine cycle (g)

3.10.7 Cumulative Heat Release

The combustion process can be explored by stabilizing CHR that gives the start of combustion and combustion duration of fuel. The CHR defines as the summation of the heat release rate. The CHR can be ascertained by the integration of the heat release rate equation with respect to the crank angle as stated below and elaborated in the HRR subhead.

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

The numerical value calculated by the below equation can be confirmed by the data obtained by enginesoft. The enginesoft is analysing the combustion data by processing the signal obtained from the cylinder pressure piezo sensor and encoder[268].

$$\int dQ = 1/(\gamma-1)\left[\int vdp + \gamma\int Pdv\right] - \int dQw$$

3.10.8. Fraction of mass burn

The heat release in the combustion or power stroke depends upon the quantity of fuel burnt during that stroke. Therefore the fraction of mass burn (FMB) in the individual cycle is scaling from 0% to 100% and represented by the value from 0 to 1. The value of FMB is increasing with a crank angle and follow the same trend which is followed by cumulative heat release. The fraction of mass burn is mostly determined with the help of a procedure developed by Rassweiler and Withrow [245]. Basically, two assumptions are considered by Rassweiler and Withrow for their procedure which is: the pressure change (Δp_j) in the cylinder occurs due to change in pressure due to change in value during the movement of the piston (Δpv_j) and pressure rise (Δpc_j). Therefore the variation in in-cylinder pressure is represented as:

$$\Delta p_j = \Delta pc_j + \Delta pv_j$$

The pressure rise rate is denoted with Δpc_j which is dependent upon the rate of heat addition w.r.t. per crank angle rotation which is fixed as discussed above. The MFB at a specific interval of time is calculated with the help of the following relation.

$$\text{MFB} = \frac{mb\ (i)}{mb\ (total)} = \frac{\Sigma\frac{i}{0}\Delta Pc}{\Sigma\frac{N}{0}\ \Delta Pc}$$

Where N = Angle of rotation for the crank.

3.11. Experimental Rule of Procedure

The manual start constant speed diesel engine was selected as a research engine in current research. Hence, the engine was started by giving sufficient momentum to the flywheel manually with the help of decompressing the lever and pressing the exhaust valve. The engine is started at no loading condition. To bring the engine from transient state to the steady state, the engine is run at least for30 minutes. The engine was started with the diesel engine and after getting a steady state it is switched to required tested fuel. To know whether steady state achieved or not the exhaust gas temperature was monitored regularly through temperature indicator which is installed on the control panel. Once the temperature becomes constant it indicates that steady state achieved. All the sensors are turned ON and the data acquisition system is connected with the personal computer. The enginesoft software is started and the system for automatic data entry is activated. All the sensors are set to run at their minimum resolution so that the data collected is near to the exact data. The inside cylinder pressure w.r.t. per angle, the crank rotation was measured and monitored through enginesoft software. For that, the average of more than 80 previous cycles was taken for every loading condition of all tested fuels. For minimizing the error for exhaust emissions, the average of 5 data was taken. The same procedure is followed for performance parameters as well. All the readings were taken for diesel fuel and take this data as a baseline. The engine is then switched to blends by using a rotary valve which is installed near the burette. As discussed earlier, two different fuel tanks are installed to avoid any change in the composition of blended fuels. One fuel take is dedicatedly given for petroleum diesel as the engine is started and switching off on the petroleum diesel. The engine is run on petroleum diesel at least for 30 minutes every starting and stopping time. The uncertainty and accuracy associated with all the measuring devices, results, and calculations are given in table 3.13.

For validation of the data, the results calculated manually, and the results obtained by enginesoft software are matched and found that both the results are identical to each other. For the validation of emissions data, the results obtained manually for petroleum diesel was compared with the standard results given with the exhaust gas analyser manual. Both the results are quite similar.

Table 3.13: Table of accuracies and uncertainties

S. No.	Measurements	Measurement Principle	Range	Accuracy
1	Engine load	Strain gauge type load cell	0-25 Kg	±0.1Kg
2	Speed	Magnetic pickup type	0-2000 rpm	±20 rpm
3	Time	Stop watch	--	±0.5%
4	Exhaust Temperature	K-type thermocouple	0-1000°C	±1^{o}C
5	Carbon monoxide	Non-dispersive infrared	0-10% vol.	±0.2%
6	Carbon dioxide	Non-dispersive infrared	0-20% vol.	±0.2%
7	Total hydrocarbons	Non-dispersive infrared	0-20,000 ppm	±2 ppm
8	Oxides of nitrogen	Electrochemical	0-4000 ppm	±15ppm
9	Smoke	Photochemical	0-100%	± 2%
10	Crank angle sensor	Optical	0-720 °CA	± 0.2^{o}CA
11	Pressure	Piezo sensor	0-200 bar	± 1 bar
Calculated results and Uncertainty				
12	Engine power	--	0-6 kW	±1.0%
13	Fuel consumption	Differential pressure	--	±2.0%
14	Air consumption	Air box with orifice	--	±1.0%
15	BTE	--	--	±1.0%
16	BSEC	--	--	±1.5%
17	Heat release	Sorenson model	--	±5.0%
18	In-cylinder temp.	Ideal gas equation	Up to 3000°K	±5.0%

The characteristics (combustion, performance, and exhaust gas emissions) of the research engine for all test fuels for a complete loading situation were analysed exhaustively. For that number of engines, trials are conducted. The engine trials were repeated several times to avoiding any uncertainty and inconsistency in the results. All the instruments and sensors were calibrated before testing hence the results are authentic and accurate.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Introduction

The various results got during the present research are presented and elucidated during the current chapter. The chapter begins with the selection of feedstocks for biodiesel production and process optimisation of biodiesel production, followed by a selection of alcohols. The effect of various parameters like molar ratio, reaction temperature, catalyst concentration, and reaction time on the yield of biodiesel production is analysed in this chapter. The blend of biodiesel and alcohols were prepared in such a way that they meet the properties of mineral diesel. After preparing the blend all the physicochemical properties were tested which are represented in the chapter. The variation in the properties of different blends is also discussed with the help of properties of all parent fuels and literature data. The prepared test fuels were then tested on an unmodified DI immobile diesel engine. Effect of these test fuels on performance, emissions, and combustion characteristics of the engine were analysed and the results are presented with detailed explanation during this chapter.

4.2. Selection of Biodiesel Feedstock and Alcohols

The properties of numerous inedible feedstocks are analysed during the literature survey. Based on that properties analysis and availability, jatropha curcas oil was selected for biodiesel production. The jatropha curcas seed was conglomerate from premises of DTU, New Delhi, and seeds were sundry on the campus itself. The seeds were then cold crush in oil impeller machine to extract the oil from them. The oil contains some impurities, so the oil is filtered with the help of filter paper and heated above 100°C for the dislodging of water contains in jatropha oil. Similar to jatropha curcas selection, the alcohols are also selected after analysing their properties during the literature review. It was found that n-butanol and n-octanol have better properties than methanol and ethanol while used for petrodiesel engine. Possessions tantamount heating value (HV) and cetane number (CN) of higher carbon alcohols such as n-butanol and n-octanol are much better than methanol and ethanol which make it better vigour supplier for the engine. Kinematic viscosity (KV) of n-butanol is less compared to biodiesel fuel so the blending of n-butanol with biodiesel diminutions density & kinematic viscosity of biodiesel and bring near petroleum diesel fuel. While lower flash point and better cetane index of n-octanol improved the combustion phenomena of biodiesel. The proportion of alcohol in the blend also kept in such a way that the better result can be obtained.

4.3. Process Optimisation of Biodiesel Production

The feedstock selected to produce biodiesel during the present study is jatropha curcas oil (JCO). The physicochemical competences of JCO are already discussed and analyse in chapter 3. The biodiesel from the jatropha oil was prepared as per the process explained in chapter 3. The process was found time consuming and costly therefore the process optimisation for biodiesel production was performed through which the optimum condition of various parameters was analysed for further biodiesel production as discussed in an earlier chapter. First of the reduction of FFA was optimised during the esterification process then the yield of biodiesel production was optimized as discussed below.

4.3.1. Process optimisation of esterification

In esterification progression, acid value (AV) of fat was alleviated because FFA available in the fat is reacted with methanol in the acidic medium. As discussed above in the present study the catalyst selected was PTSA. Four main variables were optimised in the present reaction those were catalyst concentration (A), reaction temperature (B), reaction time (C), and molar ratio (D) using central composite design. The software generates one matrix in which 30 experiments were suggested. Those 30 experiments contained 24 individual experiments, 5 repeated experiments, and one experiment without catalysts. Those 5 experiments were conducted to evaluate the error that occurred during experimentation and the influence of catalysts on FFA detraction. A list of experiments suggested by the design expert software is already discussed during chapter 3.

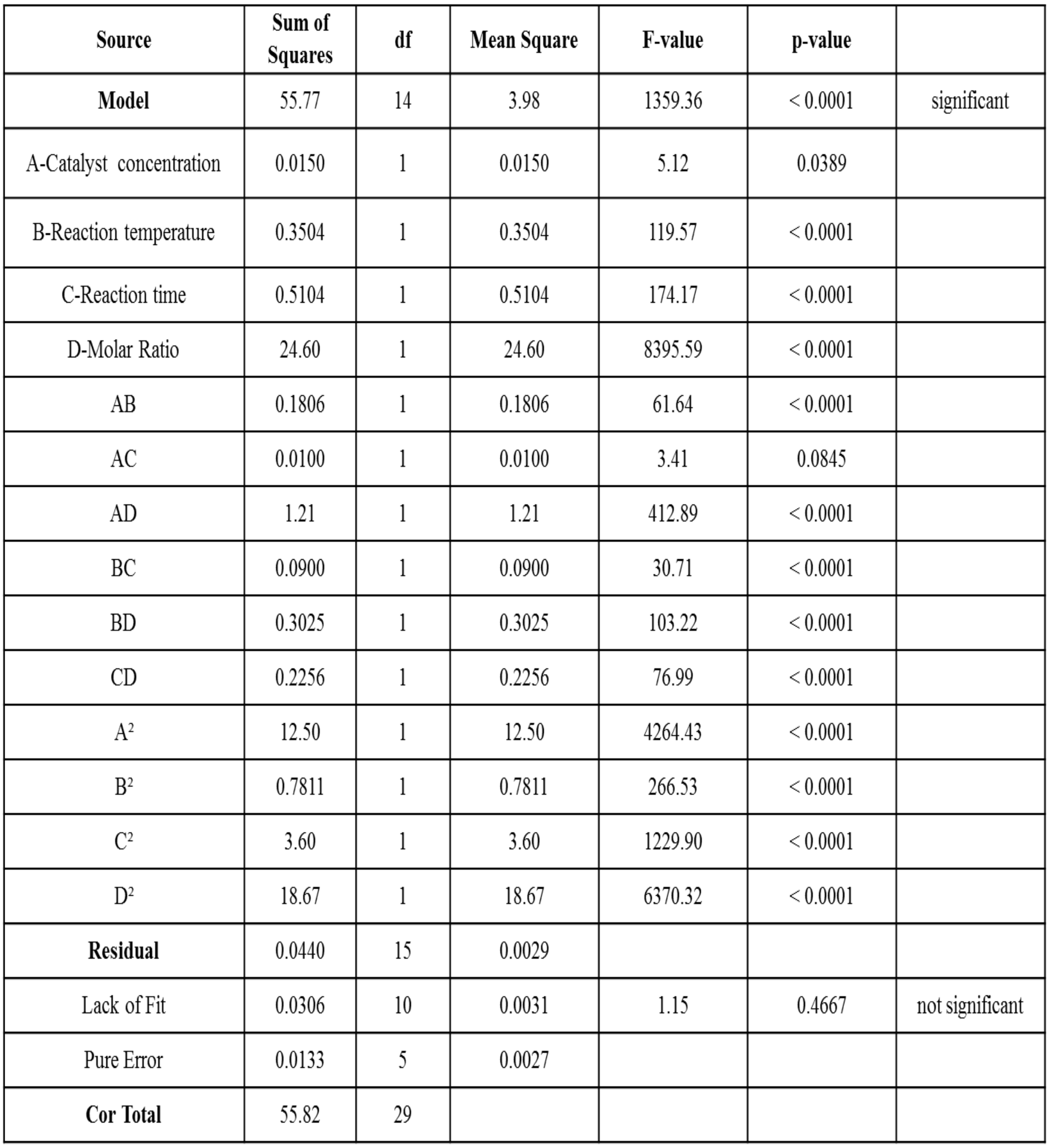
FFA of JCO was reduced from 7.1% to 1.71% during the esterification process. The optimised value of all parameters which affect the FFA reduction is discussed during this section. To evaluate the fitness of optimisation of the esterification process one model of Analysis of variance (ANOVA) was performed. The 30 experiments suggested by design experts to appraise the impression of all considerations on FFA reduction throughout esterification were performed in CASRAE as per the method described in chapter 3. The value got after experiments were inserted into the software after which the design expert software gives one optimum value of all parameters and analyse their effect on FFA reduction. Table 4.1 shows the value get during the esterification process. The result got of variance for analysis through ANOVA is shown in table 4.2.

The consequences obtained expressions effect of all four factors i.e. CC, RT, ToR, and MR on the esterification process. The results are also helpful to understand the sequence of all four parameters in which they affect the biodiesel production. The reduced quadratic model with good correlations represents the better optimum result for the esterification process.

Table 4.1: Design matrix of FFA reduction

Run	A:Catalyst Concentration	B:Reaction Temperature	C:Reaction time	D:Molar Ratio	FFA
	%(w/w)	^{0}C	Minutes	Methanol/Oil	%
1	0.5	45	90	9	3.1
2	0.5	65	30	9	2.8
3	1.5	65	90	3	4.75
4	1	55	60	12	3
5	1	55	60	6	1.7
6	1.5	45	90	9	2.75
7	0.5	45	30	9	3.2
8	1.5	45	30	3	5.5
9	2	55	60	6	4.5
10	0.5	65	90	9	2.9
11	1	75	60	6	2.15
12	1	55	60	0	7.1
13	0.5	65	30	3	4.7
14	1	55	60	6	1.7
15	1	55	0	6	3.55
16	1.5	65	30	3	5.2
17	1.5	65	30	9	2.1
18	0.5	45	90	3	4
19	0.5	65	90	3	4.5
20	1	55	120	6	2.85
21	0	55	60	6	4.4
22	1.5	65	90	9	2.2
23	1	55	60	6	1.8
24	1	35	60	6	2.7
25	0.5	45	30	3	4.65
26	1.5	45	30	9	2.95
27	1	55	60	6	1.7
28	1	55	60	6	1.8
29	1.5	45	90	3	4.8
30	1	55	60	6	1.7

Table 4.2: ANOVA analysis of FFA reduction



Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	55.77	14	3.98	1359.36	< 0.0001	significant
A-Catalyst concentration	0.0150	1	0.0150	5.12	0.0389	
B-Reaction temperature	0.3504	1	0.3504	119.57	< 0.0001	
C-Reaction time	0.5104	1	0.5104	174.17	< 0.0001	
D-Molar Ratio	24.60	1	24.60	8395.59	< 0.0001	
AB	0.1806	1	0.1806	61.64	< 0.0001	
AC	0.0100	1	0.0100	3.41	0.0845	
AD	1.21	1	1.21	412.89	< 0.0001	
BC	0.0900	1	0.0900	30.71	< 0.0001	
BD	0.3025	1	0.3025	103.22	< 0.0001	
CD	0.2256	1	0.2256	76.99	< 0.0001	
A^2	12.50	1	12.50	4264.43	< 0.0001	
B^2	0.7811	1	0.7811	266.53	< 0.0001	
C^2	3.60	1	3.60	1229.90	< 0.0001	
D^2	18.67	1	18.67	6370.32	< 0.0001	
Residual	0.0440	15	0.0029			
Lack of Fit	0.0306	10	0.0031	1.15	0.4667	not significant
Pure Error	0.0133	5	0.0027			
Cor Total	55.82	29				

In ANOVA result the individual effect of various parameters is given. The higher F-value 8395.59 of the model was a sign of the significance of the quadratic model. At the same time, a p-value of the model was obtained less than 0.0001 which was much lower than 0.05

this again showed the significance of the corresponding model term [269]. The higher F-value for all variables showed a linear term for these variables for FFA reduction.

In linear terms, the highest F-value of molar ratio& p-value less than 0.0001 which signalize the effect of the molar ratio was highest in FFA reduction. The sequence of F-values in linear terms for the various parameter was the molar ratio, reaction time, reaction temperature, and catalyst concentration. However, the p-value for all the parameters remains less than 0.05. This indicates that the molar ratio put more effect among all parameters followed by reaction time, reaction temperature, and catalyst concentration. Furthermore, the lower F-value of 1.15 for lack of fit indicates that it was not significant as compared to pure error [270].

The fit statistics for the esterification process represents various important value is shown in table 4.3. In the optimisation process, the R^2 value of the model represents the variation of the calculated amount around the mean value. The value of R^2 in the present steady was 0.9992 which was sufficiently high for showing the significance. However higher value of R^2 misleads sometime that model was significant as its value increase with adding of factors. On the other hand value of predicted R^2 need not increase with adding of factors. The value of predicted R^2 during esterification was 0.9965 which indicates the model was significant and effective for the esterification process. Furthermore, the value of adjusted R^2 was 0.9985 which shows a reasonable agreement with predicted R^2 value. The higher value of predicted R^2, adjusted $R^{2,}$ and R^2 proves that the model was a higher level of significance.

Table 4.3: Fit Statistics

Std. Dev.	0.0541	**R²**	0.9992
Mean	3.36	**Adjusted R²**	0.9985
C.V. %	1.61	**Predicted R²**	0.9965
		Adeq Precision	139.1104

The sequence of all parameters was analysed from the ANOVA response table. The equation 4.1 represents the FFA value after process optimisation of esterification in term of code factors.

$$\mathbf{FFA} = +1.73 + 0.0250*A - 0.1208*B - 0.1458*C - 1.01*D - 0.1062*AB - 0.0250*AC - 0.2750*AD + 0.0750*BC - 0.1375*BD + 0.1187*CD + 0.6750*A^{2} + 0.1687*B^{2} + 0.3625*C^{2} + 0.8250*D^{2} \qquad (4.1)$$

The same reaction is represented with their actual parameters in equation 4.2.

$$\text{FFA} = +\ 14.63802 - 2.98125 * \text{Catalyst Concentration} - 0.163958 * \text{Reaction Temperature} - 0.073194 * \text{Reaction time} - 1.08125 * \text{Molar Ratio} - 0.021250 * \text{Catalyst Concentration} * \text{Reaction Temperature} - 0.001667 * \text{Catalyst Concentration} * \text{Reaction time} - 0.183333 * \text{Catalyst Concentration} * \text{Molar Ratio} + 0.000250 * \text{Reaction Temperature} * \text{Reaction time} - 0.004583 * \text{Reaction Temperature} * \text{Molar Ratio} + 0.001319 * \text{Reaction time} * \text{Molar Ratio} + 2.70000 * \text{Catalyst Concentration}^{2} + 0.001688 * \text{Reaction Temperature}^{2} + 0.000403 * \text{Reaction time}^{2} + 0.091667 * \text{Molar Ratio}^{2} \qquad (4.2)$$

The adequacy of the model was evaluated by determining the distribution of residuals in the starting. Some deviation in residuals values between predicted and actual can come which guide to tracking customary dissemination only if the model contains random experimental errors [271]. Therefore, the externally studentized residual predicted v/s normal % probability is presented in figure 4.1. The graph follows an orthodox track and epitomises the externally studentized residuals follow a normal distribution in the model. If the externally studentized residual restricted to track normal distribution curve takes the shape of “S’’[271].

Another graph was plotted between predicted values of FFA to the experimental value of FFA for a particular parameter value is shown in figure 4.2. This graph also follows the linear line between predicted FFA value and experimental FFA value. This graph was plotted by submitting the FFA values which got after conducting the experiments suggested by the design expert. Then the software analyse the effect of various parameters on FFA reduction during esterification and calculates the FFA value as per the result. Both experimental and predicted data were taken and the graph was plotted. The linear relationship between predicted and experimental data showed that the model was well designed and a good fit for the condition.

The response graph was plotted for all variables which affect the FFA reduction during the esterification process. The main graph showed the interaction of various parameters during desirability and actual FFA reduction in figure 4.3. The perturbation plot helps to compare the effects of all the factors at a particular point in the design space. The response was plotted by changing only one factor over its range while holding all the other factors constant. By default, Design-Expert sets the reference point at the midpoint (coded 0) of all the factors as depicted in figure4.3. The interaction of various variables in three dimension representations in a combination of each other when the other two variables were fixed for optimum reduction of FFA content in the jatropha oil represents in figure 4.4 to figure 4.9. Figure 4.4 to 4.9 show the relation between two variable which affect the variation of FFA while two other variables kept constant.

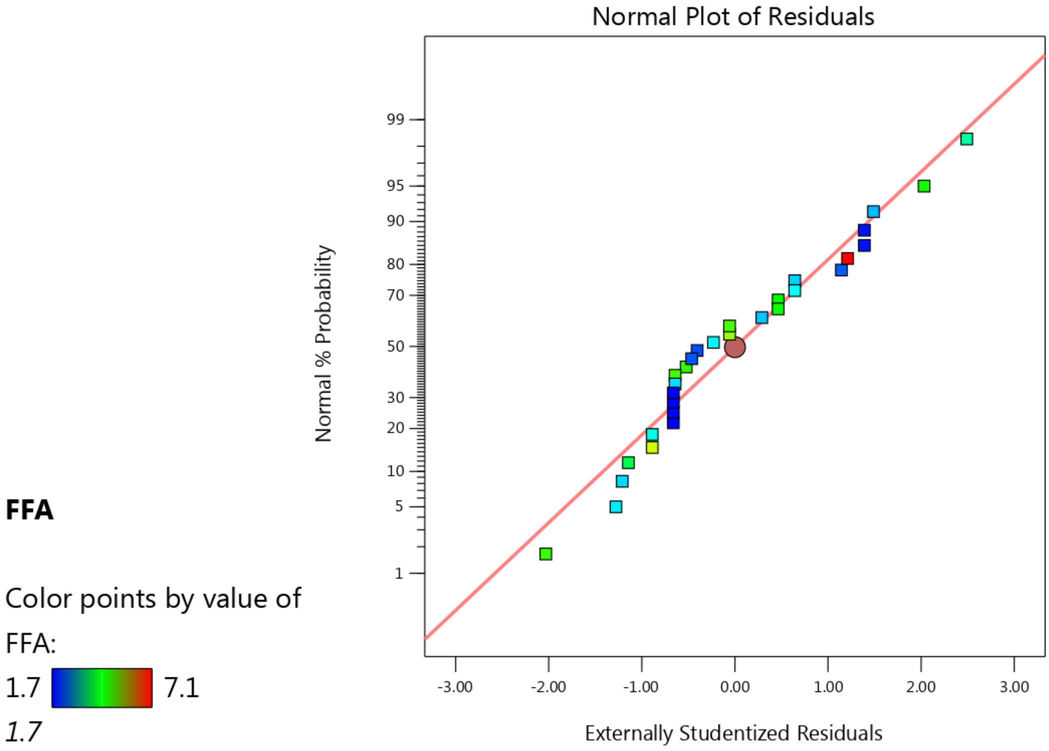


Figure 4.1: Externally studentized residuals vs. normal % probability

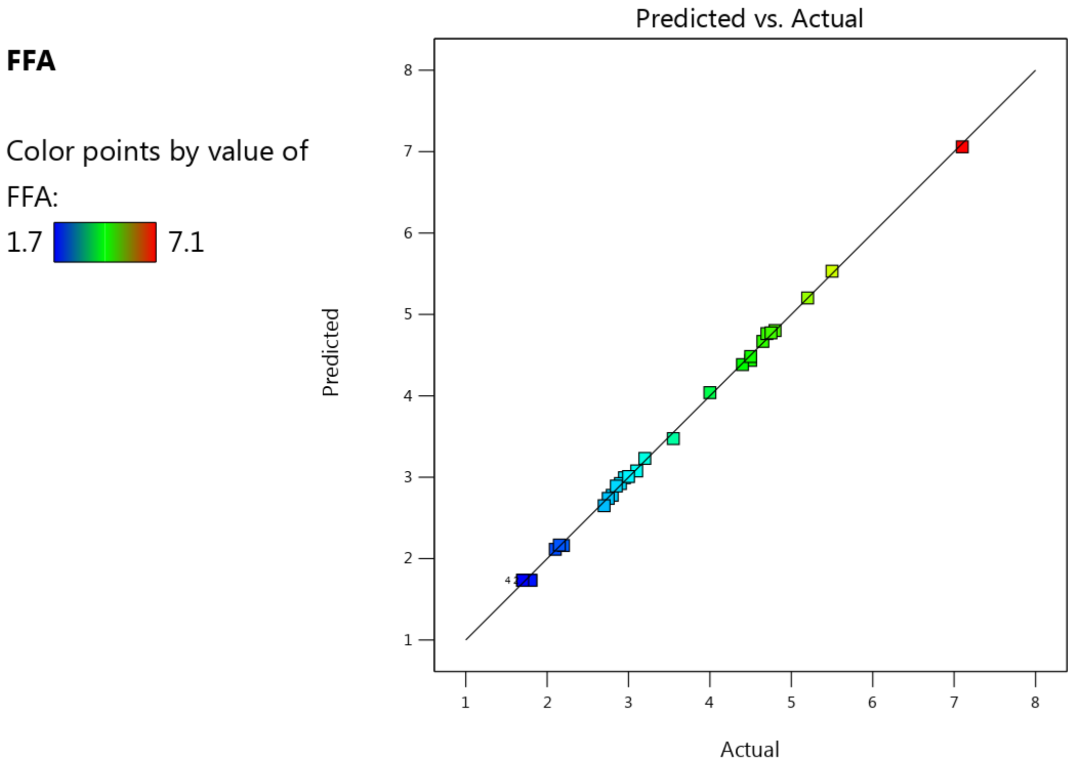


Figure 4.2: Predicted value vs. actual values.

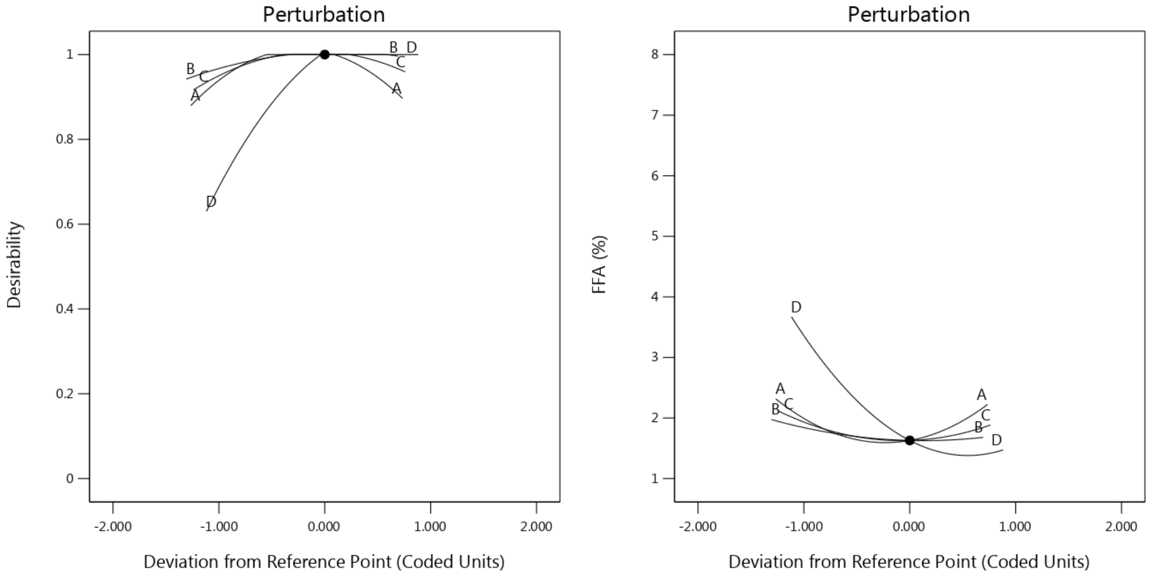


Figure 4.3: Perturbation Graph

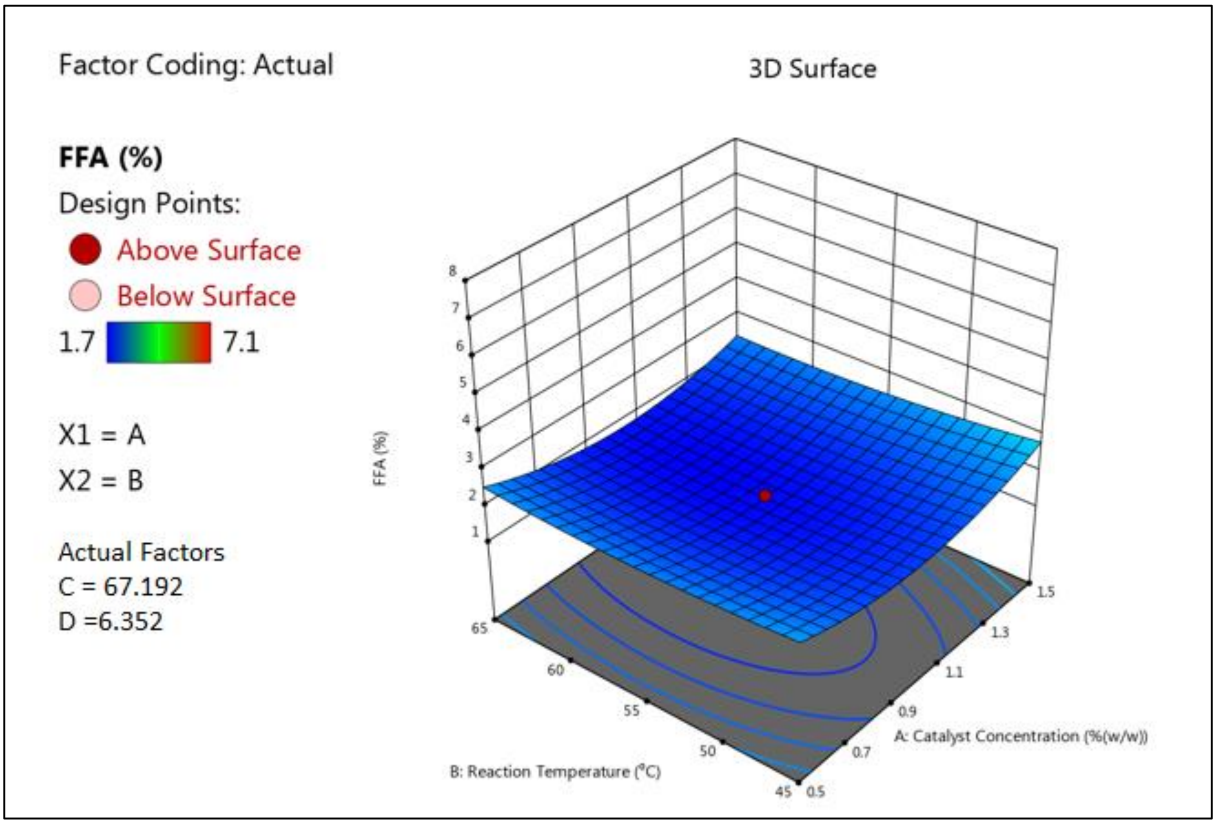


Figure 4.4: Effect of reaction temperature and catalyst concentration

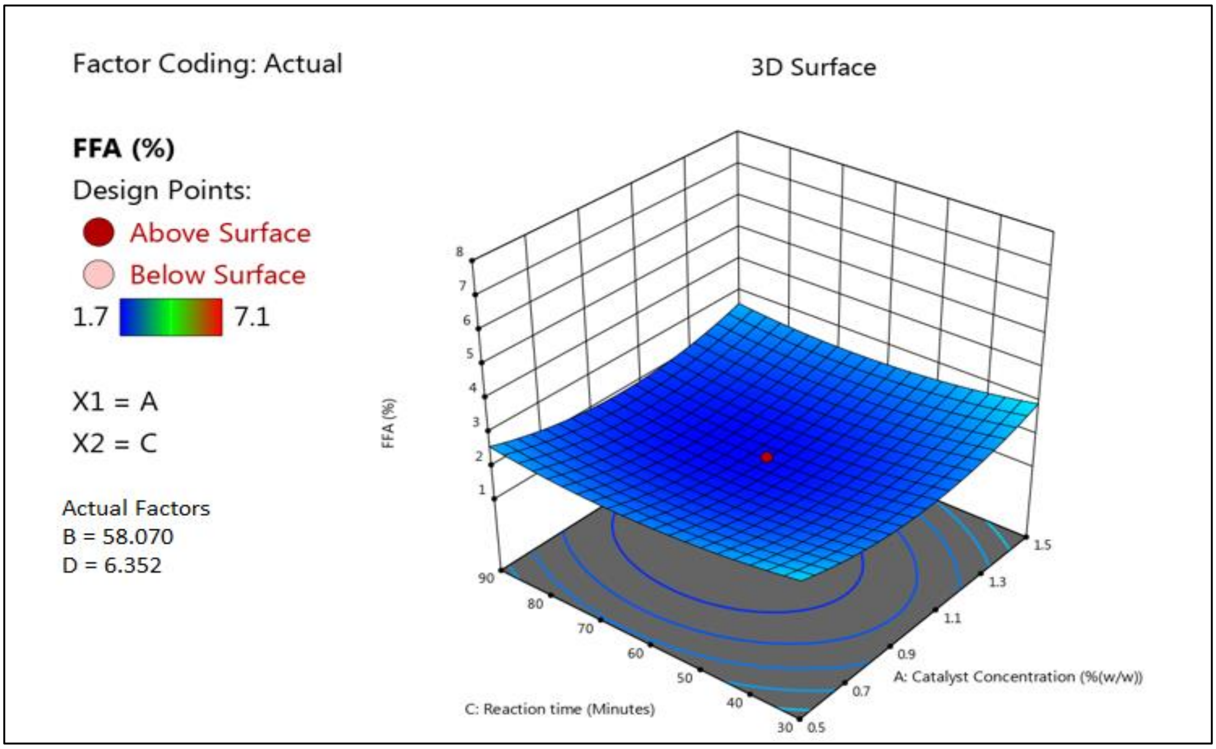


Figure 4.5: Effect of reaction time and catalyst concentration

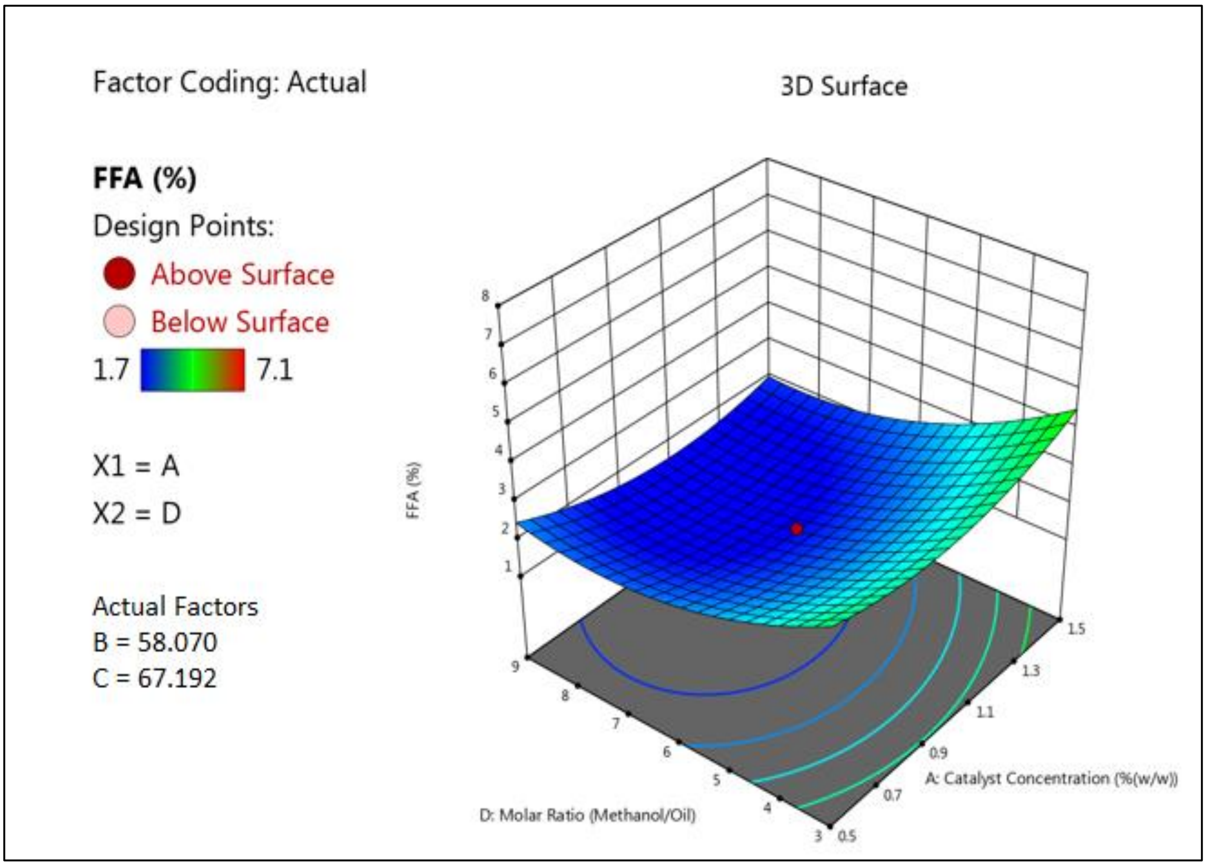


Figure 4.6: Effect of molar ratio and catalyst concentration

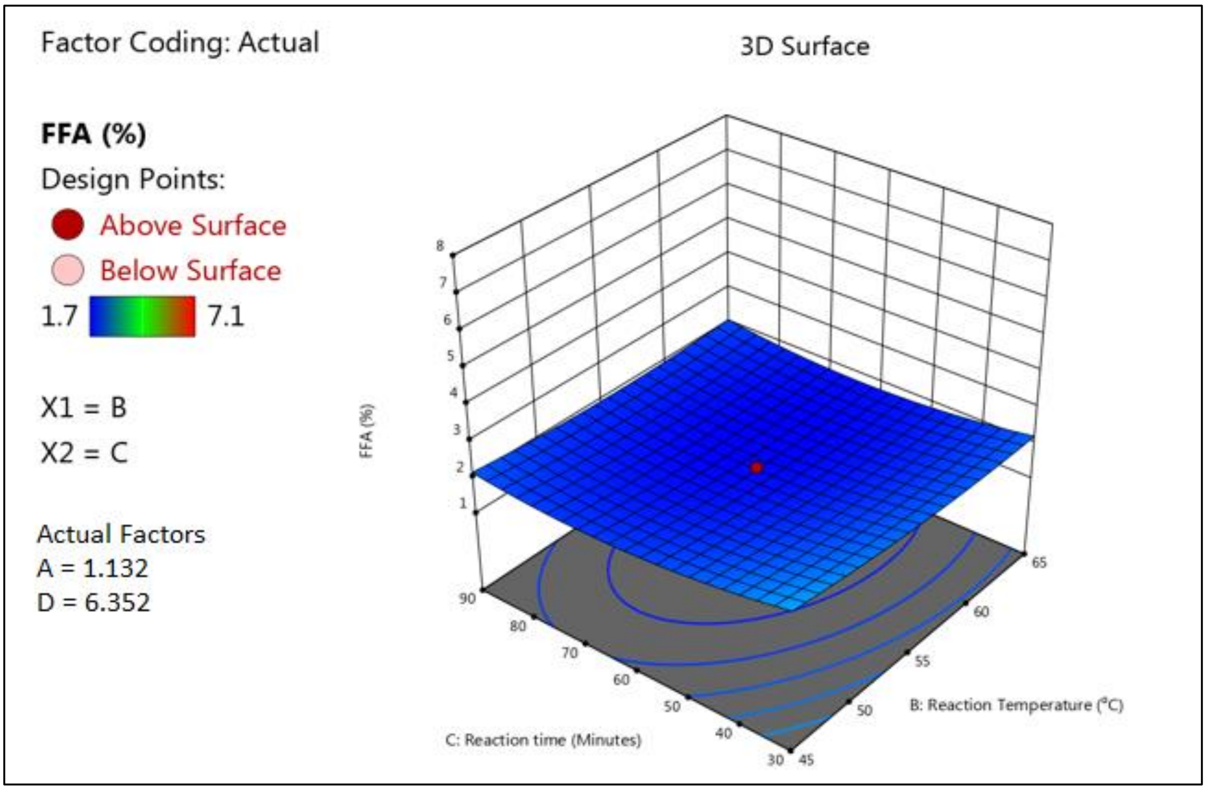


Figure 4.7: Effect of reaction time and reaction temperature

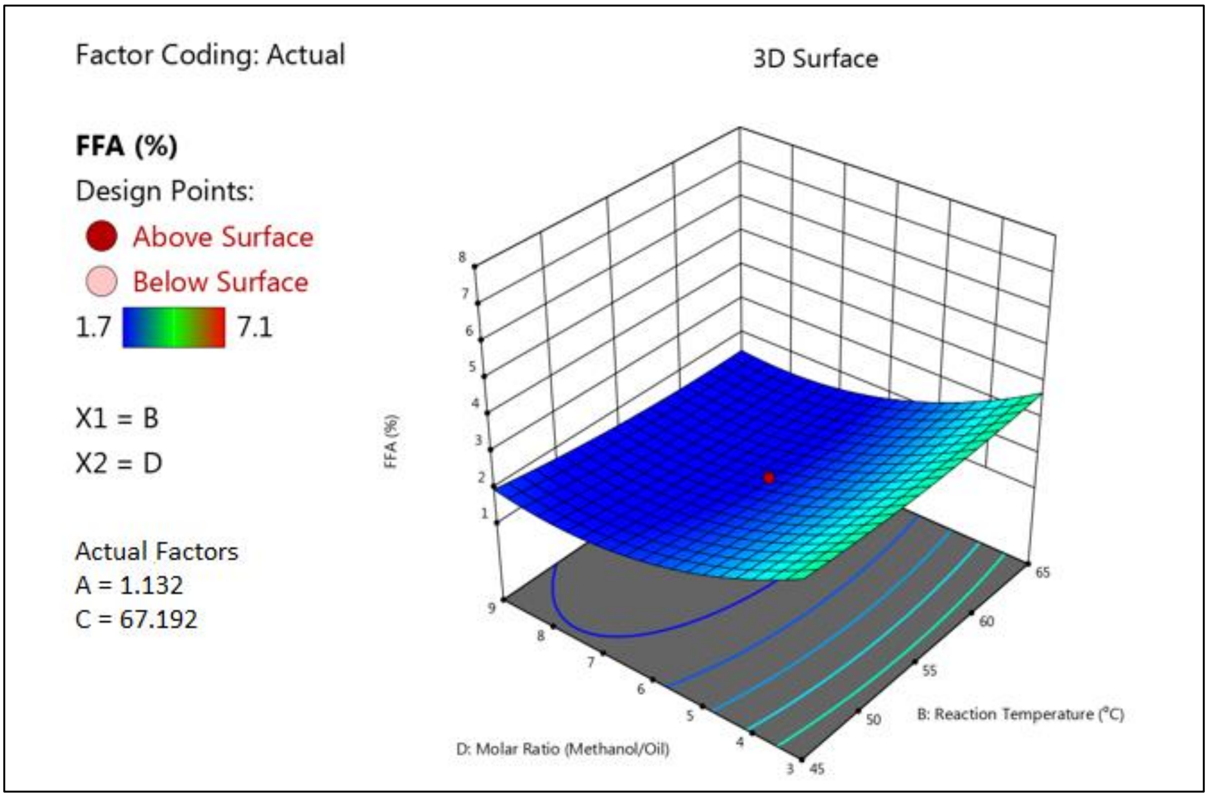


Figure 4.8: Effect of molar ratio and reaction temperature

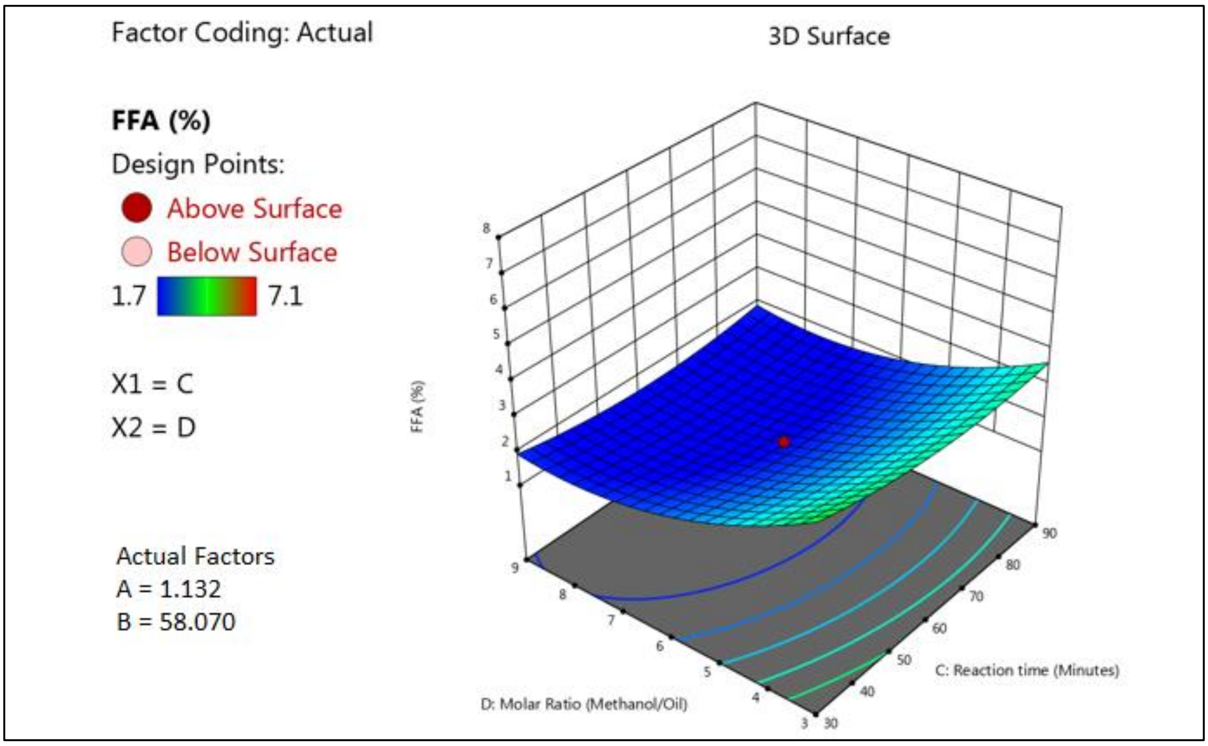


Figure 4.9: Effect of molar ratio and reaction time

The ramp function of the esterification process conducted to reduce the FFA percentage in JCO is revealed in figure 4.10. The ramp function shows the range of all the variables in which the optimum value is highlighted through a point. This point of all the parameters is considered for an optimum process for FFA reduction. It was found that by taking a catalyst concentration of 1.13237, reaction temperature of 58.0701°C, reaction time of 67.1923 minutes, and molar ratio of 6.35247 the FFA of JCO can be abridged starting 7.1% to 1.6295%. However, those values were difficult to maintain therefore nearest whole number to the value was considered for the experiment. After the experiment, the FFA of the jatropha oil was found near 1.7% only which was again rationalised the significance of archetypal. Factor coding of experimental results was developed by the software which represents the range of the parameters for the significant fit model. The factor coding of the esterification process is given in figure 4.11.

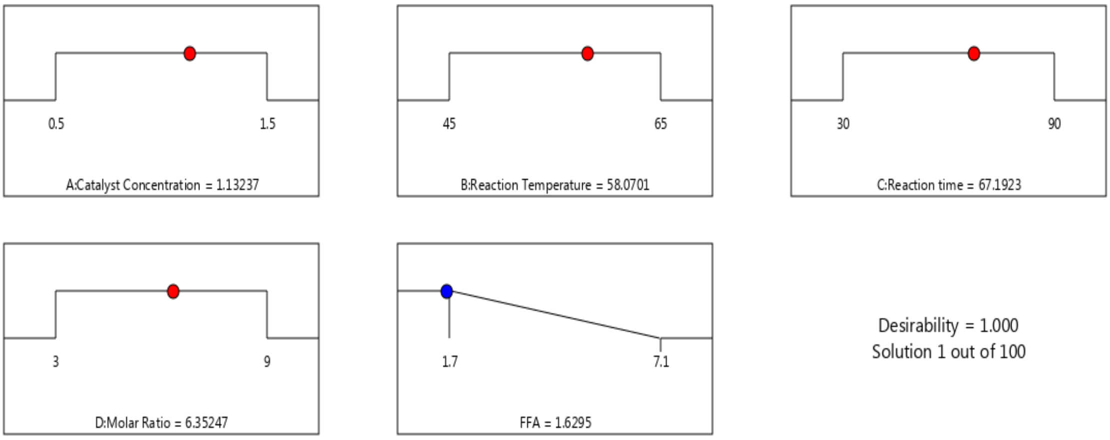


Figure 4.10: Ramp function of the esterification process

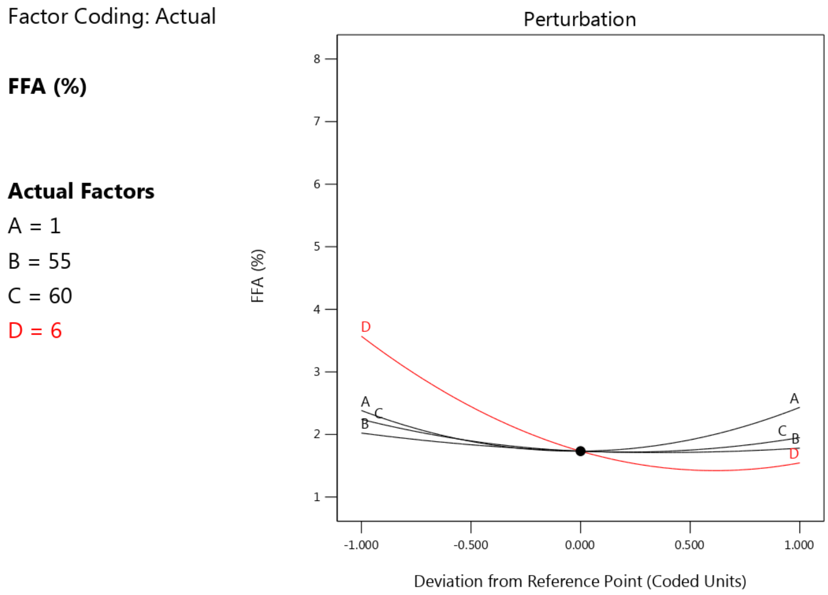


Figure 4.11: Factor coding for the esterification process.

4.3.2. Process optimisation for transesterification

The biodiesel of high FFA content JCO was prepared through alkaline transesterification which took place in two stages. In the first stage, the FFA percentage in JCO was reduced by 7.1% to 1.7% through acidic esterification. The low FFA JCO was converted into biodiesel in the second stage during this treated JCO reacted with methanol in a catalytic medium. The catalyst used for the present study was KOH. The complete process of biodiesel production was optimised. In the current section, the optimisation for the transesterification process was conducted in which the methanol & KOH were utilised. In esterification, the FFA of the oil was reduced however in the transesterification process the yield of the biodiesel was maximised along with the further reduction in FFA

The low FFA jatropha oil after esterification was transformed into biodiesel utilising transesterification progression. Similar to the esterification process mainly four variables were optimised as shown in table 4.4.

Table 4.4: List of all variables with their units.

S. No.	Name of Parameter	Represented With	Units
1.	Catalyst Concentration	(A)	w/w
2.	Reaction Temperature	(B)	°C
3.	Reaction Time	(C)	Minutes
4.	Molar Ratio	(D)	Methanol/Oil

The optimisation of yield during the transesterification process the methodology used was central composite design. Similar to the esterification process, for the transesterification process as well the software created a matrix that contains a total of 30 experiments. Out of 30 runs, one has a negative value of one variable so that experiment cannot be performed. Now 29 experiments consist of 24 individual experiments with 5 repeated experiments. The 5 experiments were performed to evaluate the error that occurs during experimentation. The list of experiments suggested by the design expert software is already discussed during chapter 3.

The yield of jatropha biodiesel was optimised during this process so that the overall price of biodiesel might be abridged & quality biodiesel can be produced. To evaluate the fitness of optimisation of the transesterification process single model of Analysis of variance (ANOVA) was implemented. A total of 29 experiments suggested by design experts to appraise possessions of all constraints on maximising the yield of biodiesel during transesterification were performed in CASRAE as per the method described in chapter 3. The value got after experiments were feed into the software after which the design expert software gave one optimum value of all parameters and analysed their effect on the maximisation of yield. Table 4.5 shows the actual yield got during biodiesel production for all the set of experiments suggested by the design experts. That data was feed to deign expert after which the calculation was done by a software by taking the CCD model as a reference. The software generated the relationship of all the parameters in linear and quadratic terms for their effect on yield. The software determined the significance of all parameters for increasing the yield of biodiesel and given in the form of the table also known as ANOVA table. The result got of variance for analysis through ANOVA is shown in table 4.6.

Table 4.5: Design matrix of transesterification

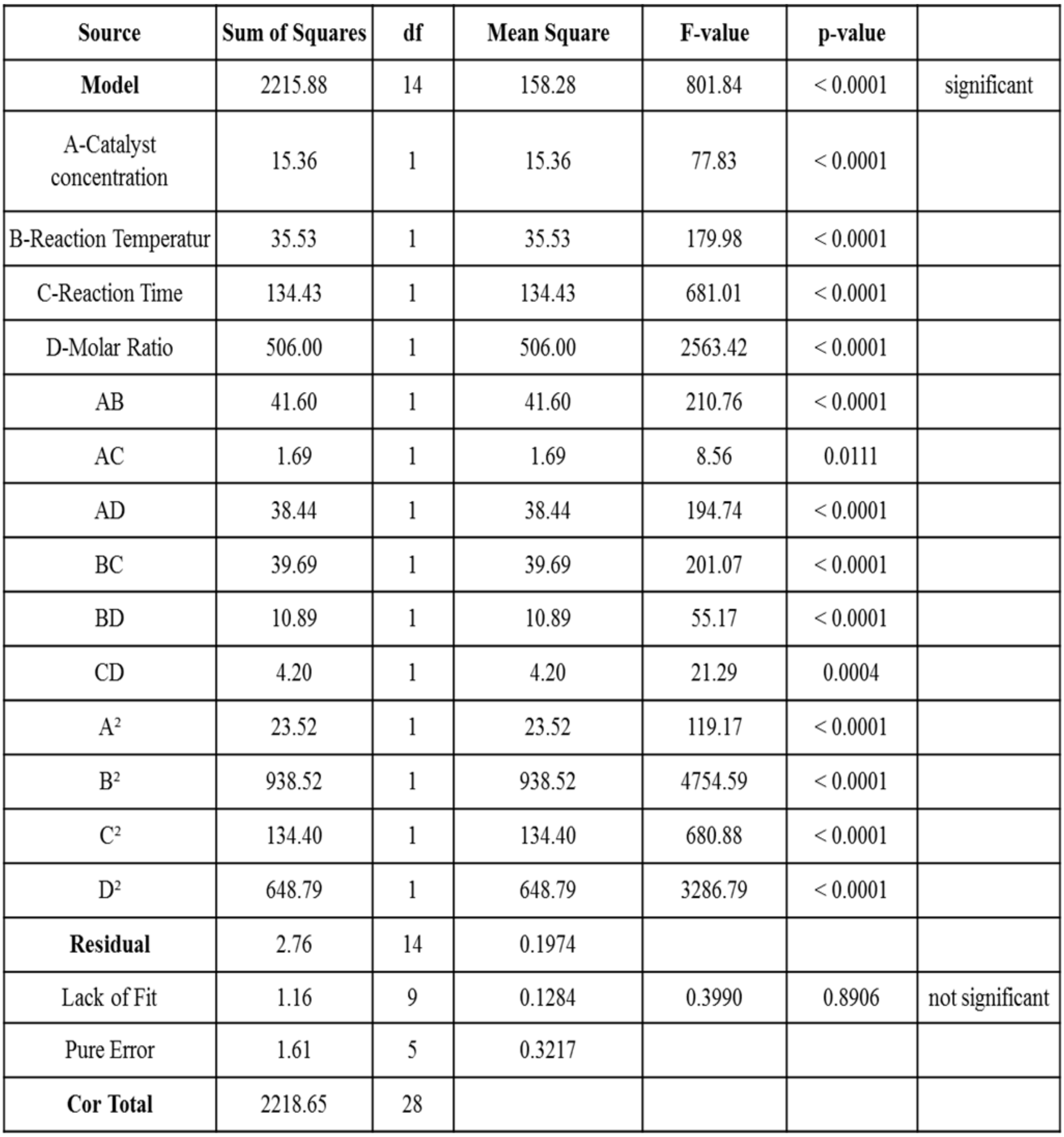
Run	A:Catalyst concentration	B:Reaction Temperature	C:Reaction Time	D:Molar Ratio	Yield
	%(w/w)	^{0}C	Minutes	Methanol/Oil	%
1	0.25	40	30	9	85.7
2	0.25	40	30	3	77
3	0.25	40	90	3	79
4	0.75	55	60	12	85.5
5	1.25	70	30	3	67.5
6	0.25	40	90	9	86
7	-0.25	55	60	6	
8	1.25	40	90	3	78
9	1.25	70	30	9	79
10	0.75	85	60	6	69.5
11	0.75	55	60	6	96.3
12	0.75	55	60	6	96.5
13	0.25	70	30	9	82
14	1.25	70	90	3	77
15	1.25	70	90	9	87
16	0.75	25	60	6	74.5
17	1.25	40	90	9	90.5
18	1.75	55	60	6	89
19	0.25	70	30	3	76.5
20	0.75	55	60	0	66.5
21	0.75	55	60	6	95
22	1.25	40	30	9	89.5
23	0.25	70	90	3	85
24	0.75	55	120	6	91.5
25	0.75	55	60	6	95.5
26	0.75	55	60	6	95.5
27	1.25	40	30	3	75
28	0.75	55	60	6	95.5
29	0.75	55	0	6	82
30	0.25	70	90	9	87.5

Results obtained showed the effect of all four constraints i.e. CC, RT, ToR, and MR on the biodiesel yield. Consequences were also helpful to understand the sequence of all four parameters in which they affect the biodiesel yield. The reduced quadratic model with good correlations represents the better optimum result for the transesterification process. In ANOVA result the individual effect of various parameters was given. The higher F-value 801.84 of the model was a sign of the significance of the quadratic model. At the same time, a p-value of the model was obtained 0.0001 which was much lower than 0.05 which again showed the significance of the corresponding model term [269]. The higher F-value for all variables showed a linear term for these variables for FFA reduction.

However, the p-value for all the parameters remains less than 0.05 for linear as well as quadratic modeling. That indicated that the model was significant. Furthermore, the lower F-value of 0.3990 for lack of fit indicated that it was not significant as compared to pure error [270].

The fit statistics for the transesterification process represent various important values which are shown in table 4.7. In the optimisation process, the R^2 value of the model represents the variation of the calculated amount around the mean value. The value of R^2 in the present steady was 0.9988 which was sufficiently high for showing the significance. However the higher value of R^2misleads some time that model was significant as its value increase with adding of factors. On the other hand value of predicted R^2 need not increase with adding of factors. The value of predicted R^2 during optimising biodiesel yield was 0.9956 which indicates the model was significant and effective for the transesterification process. Furthermore, the value of adjusted R^2 was 0.9975 which showed reasonable agreement with predicted R^2 value. The higher value of predicted R^2, adjusted $R^{2,}$ and R^2 proved that the model was a higher level of significance.

Table 4.6: ANOVA analysis of Transesterification



Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2215.88	14	158.28	801.84	< 0.0001	significant
A-Catalyst concentration	15.36	1	15.36	77.83	< 0.0001	
B-Reaction Temperatur	35.53	1	35.53	179.98	< 0.0001	
C-Reaction Time	134.43	1	134.43	681.01	< 0.0001	
D-Molar Ratio	506.00	1	506.00	2563.42	< 0.0001	
AB	41.60	1	41.60	210.76	< 0.0001	
AC	1.69	1	1.69	8.56	0.0111	
AD	38.44	1	38.44	194.74	< 0.0001	
BC	39.69	1	39.69	201.07	< 0.0001	
BD	10.89	1	10.89	55.17	< 0.0001	
CD	4.20	1	4.20	21.29	0.0004	
A^2	23.52	1	23.52	119.17	< 0.0001	
B^2	938.52	1	938.52	4754.59	< 0.0001	
C^2	134.40	1	134.40	680.88	< 0.0001	
D^2	648.79	1	648.79	3286.79	< 0.0001	
Residual	2.76	14	0.1974			
Lack of Fit	1.16	9	0.1284	0.3990	0.8906	not significant
Pure Error	1.61	5	0.3217			
Cor Total	2218.65	28				

Table 4.7: Fit Statistics

Std. Dev.	0.4443	**R^2**	0.9988
Mean	83.97	**Adjusted R^2**	0.9975
C.V. %	0.5291	**Predicted R^2**	0.9956
		Adeq Precision	90.4869

The sequence of all parameters was analysed from the ANOVA response table. The final equation in terms of code factor, equation 4.3 represents the yield of biodiesel after process optimisation of transesterification in term of code factors. However, the final equation as per the actual factor is represented by equation 4.4.

$$\text{Yield} = 95.72 - 0.9467 * A - 1.22 * B + 2.37 * C + 4.59 * D - 1.61 * AB + 0.3250 * AC + 1.55 * AD + 1.58 * BC - 0.8250 * BD - 0.5125 * CD - 1.21\, A^2 - 5.93 * B^2 - 2.24\, C^2 - 4.93 * D^2 \qquad (4.3)$$

Equation 4.3 represented with their actual parameters in equation 4.4 and equation.

$$\text{Yield} = -23.30993 + 9.70667 * \text{Catalyst concentration} + 2.88047 * \text{Reaction Temperature} + 0.203639 * \text{Reaction Time} + 8.68222 * \text{Molar Ratio} - 0.215000 * \text{Catalyst concentration} * \text{Reaction Temperature} + 0.021667 * \text{Catalyst concentration} * \text{Reaction Time} + 1.03333 * \text{Catalyst concentration} * \text{Molar Ratio} + 0.003500 * \text{Reaction Temperature} * \text{Reaction Time} - 0.018333 * \text{Reaction Temperature} * \text{Molar Ratio} - 0.005694 * \text{Reaction Time} * \text{Molar Ratio} - 4.85000 * \text{Catalyst concentration}^2 - 0.026367 * \text{Reaction Temperatur}^2 - 0.002494 * \text{Reaction Time}^2 - 0.548056 * \text{Molar Ratio}^2 \qquad (4.4)$$

The adequacy of the model was evaluated by determining the distribution of residuals in the starting. Some deviation in residuals values between predicted and actual can come which guide shadow normal distribution only if the model contains random investigational inaccuracies [271]. Therefore, the externally studentized residual predicted v/s normal % probability presented in figure 4.12. The presented graph follows a straight curve representing externally studentized lingering follow a normal distribution in the model. If the externally studentized residual dissatisfy normal distribution the curve takes the shape of “S”[271].Another graph was plotted between predicted values of yield to the experimental value of the yield of biodiesel for a particular parameter value is shown in figure 4.13. This graph also follows the linear line between the predicted yield and the yield got from the experiment.

This graph was plotted by substituting the biodiesel yield which got after conducting the experiments on the value of the parameter suggested by the design expert. The software then analysed the effect of various parameters on optimising yield during transesterification and calculate the yield as per the result. Both experimental and predicted data were taken and the graph was plotted. The linear relationship between predicted and experimental data showed that the model was well designed and a good fit for the condition. The graph was plotted as per the values shown in table 4.8.

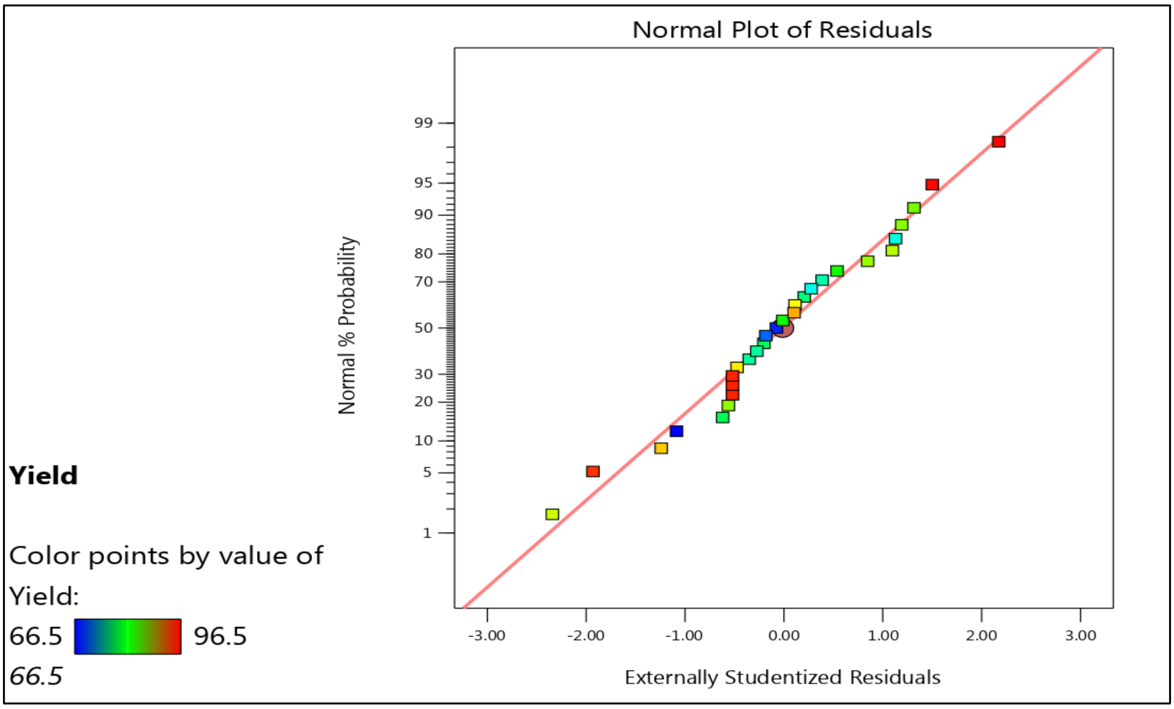


Figure 4.12: Externally studentized residuals vs. normal % probability

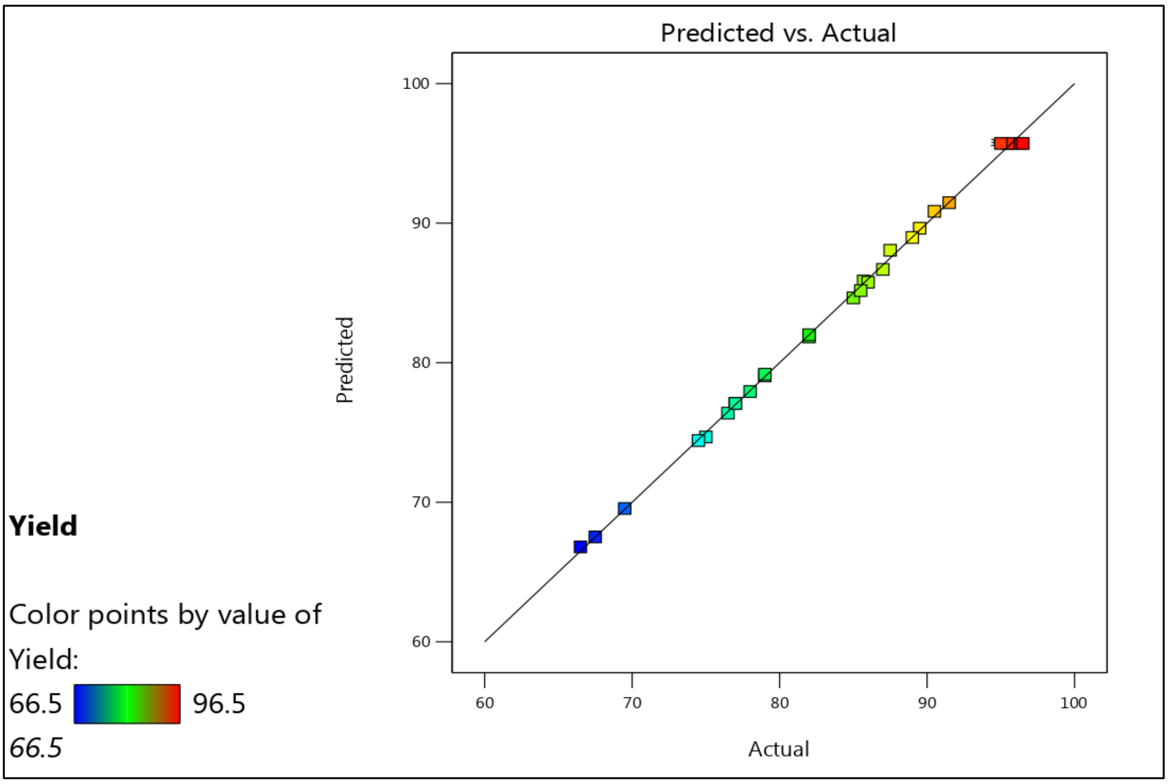
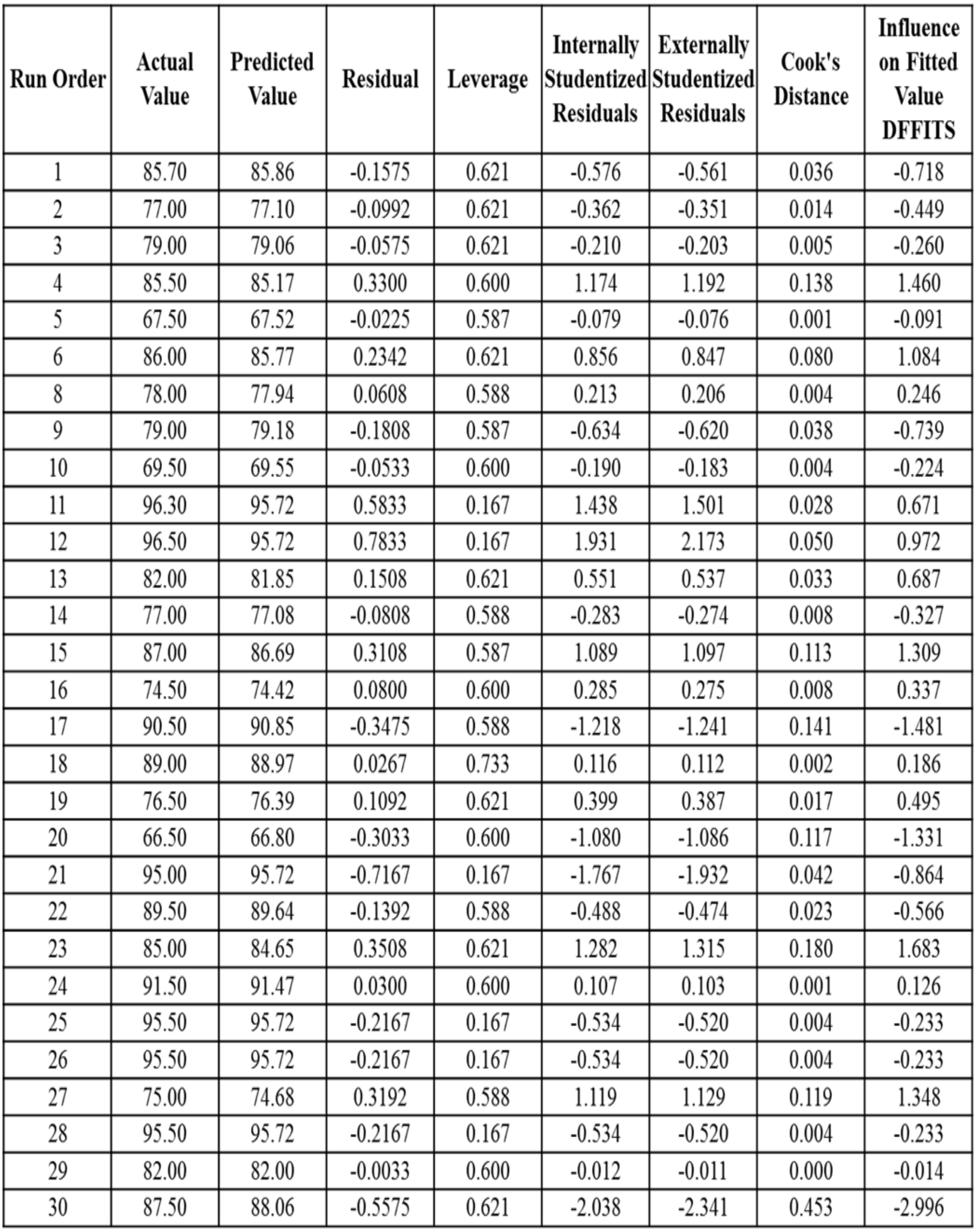


Figure 4.13: Predicted values vs. actual values of yield.

Table 4.8: Actual and predicted yields with their residuals



Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS
1	85.70	85.86	-0.1575	0.621	-0.576	-0.561	0.036	-0.718
2	77.00	77.10	-0.0992	0.621	-0.362	-0.351	0.014	-0.449
3	79.00	79.06	-0.0575	0.621	-0.210	-0.203	0.005	-0.260
4	85.50	85.17	0.3300	0.600	1.174	1.192	0.138	1.460
5	67.50	67.52	-0.0225	0.587	-0.079	-0.076	0.001	-0.091
6	86.00	85.77	0.2342	0.621	0.856	0.847	0.080	1.084
8	78.00	77.94	0.0608	0.588	0.213	0.206	0.004	0.246
9	79.00	79.18	-0.1808	0.587	-0.634	-0.620	0.038	-0.739
10	69.50	69.55	-0.0533	0.600	-0.190	-0.183	0.004	-0.224
11	96.30	95.72	0.5833	0.167	1.438	1.501	0.028	0.671
12	96.50	95.72	0.7833	0.167	1.931	2.173	0.050	0.972
13	82.00	81.85	0.1508	0.621	0.551	0.537	0.033	0.687
14	77.00	77.08	-0.0808	0.588	-0.283	-0.274	0.008	-0.327
15	87.00	86.69	0.3108	0.587	1.089	1.097	0.113	1.309
16	74.50	74.42	0.0800	0.600	0.285	0.275	0.008	0.337
17	90.50	90.85	-0.3475	0.588	-1.218	-1.241	0.141	-1.481
18	89.00	88.97	0.0267	0.733	0.116	0.112	0.002	0.186
19	76.50	76.39	0.1092	0.621	0.399	0.387	0.017	0.495
20	66.50	66.80	-0.3033	0.600	-1.080	-1.086	0.117	-1.331
21	95.00	95.72	-0.7167	0.167	-1.767	-1.932	0.042	-0.864
22	89.50	89.64	-0.1392	0.588	-0.488	-0.474	0.023	-0.566
23	85.00	84.65	0.3508	0.621	1.282	1.315	0.180	1.683
24	91.50	91.47	0.0300	0.600	0.107	0.103	0.001	0.126
25	95.50	95.72	-0.2167	0.167	-0.534	-0.520	0.004	-0.233
26	95.50	95.72	-0.2167	0.167	-0.534	-0.520	0.004	-0.233
27	75.00	74.68	0.3192	0.588	1.119	1.129	0.119	1.348
28	95.50	95.72	-0.2167	0.167	-0.534	-0.520	0.004	-0.233
29	82.00	82.00	-0.0033	0.600	-0.012	-0.011	0.000	-0.014
30	87.50	88.06	-0.5575	0.621	-2.038	-2.341	0.453	-2.996

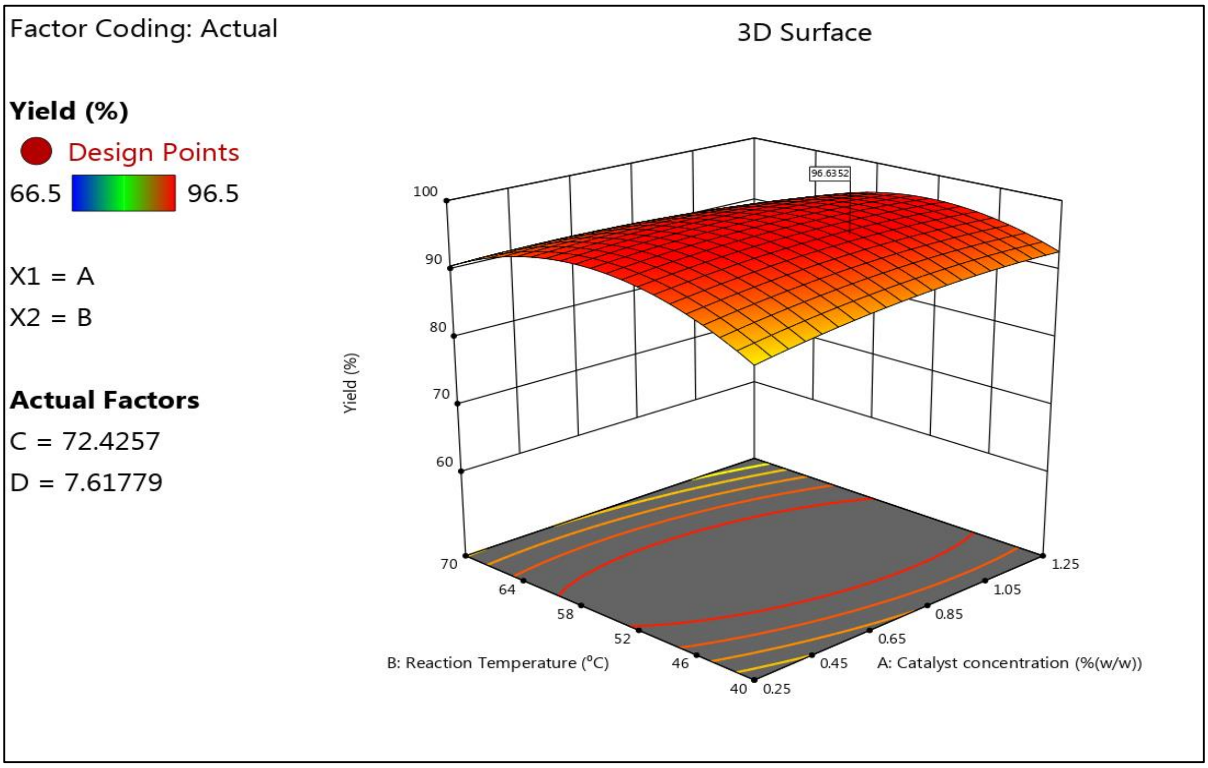


Figure 4.14: Effect of reaction temperature and catalyst concentration

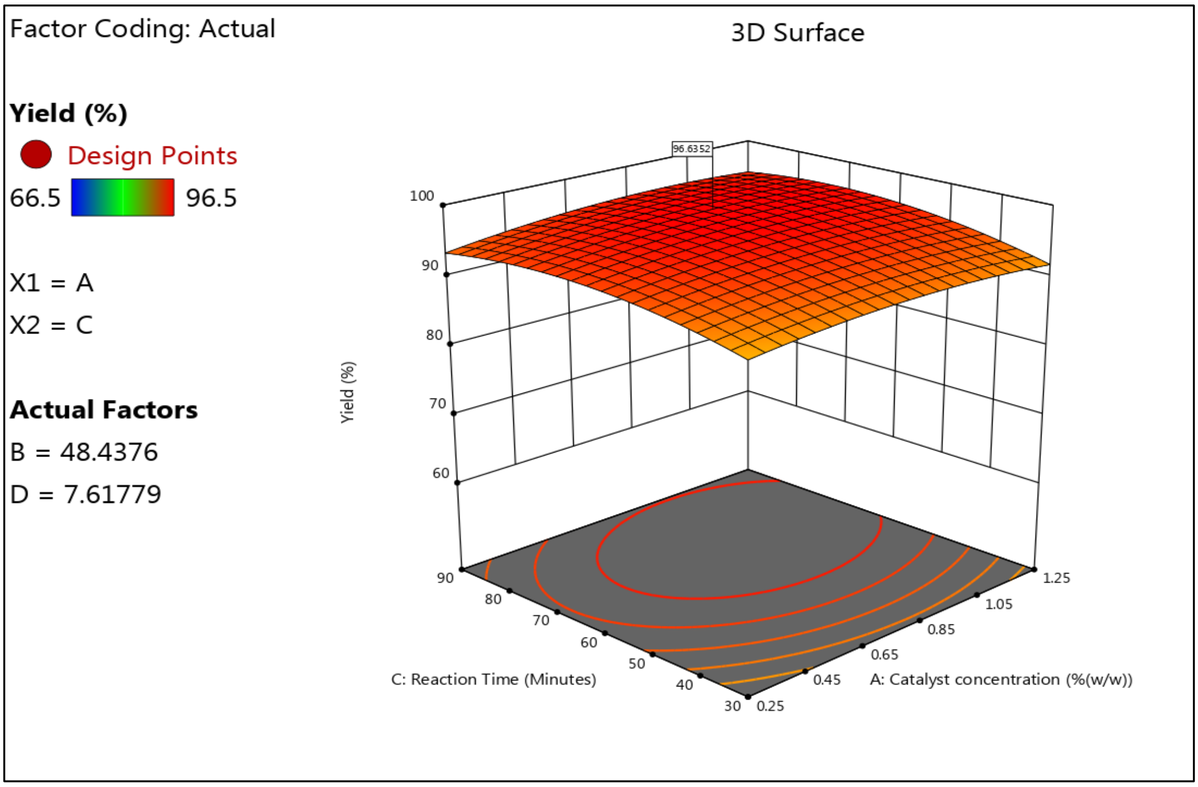


Figure 4.15: Effect of reaction time and catalyst concentration

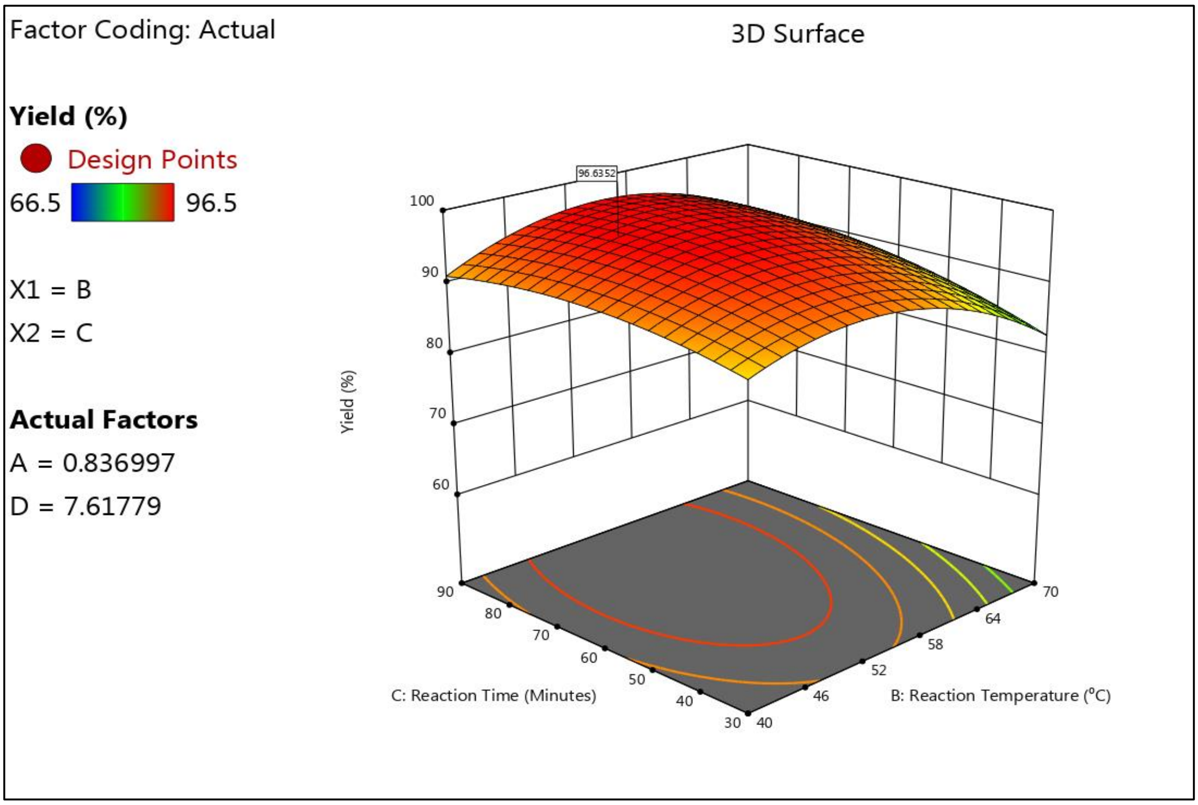


Figure 4.16: Effect of reaction time and reaction temperature

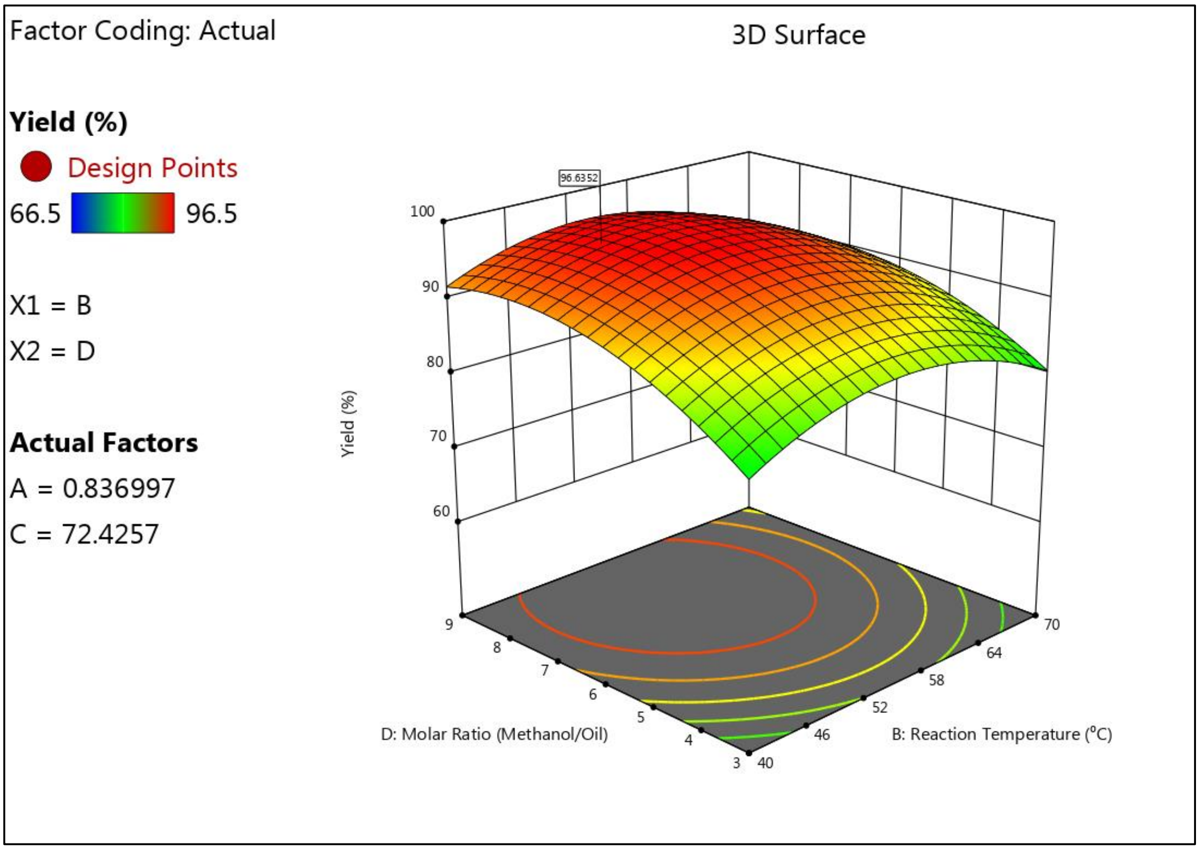


Figure 4.17: Effect of molar ratio and reaction temperature

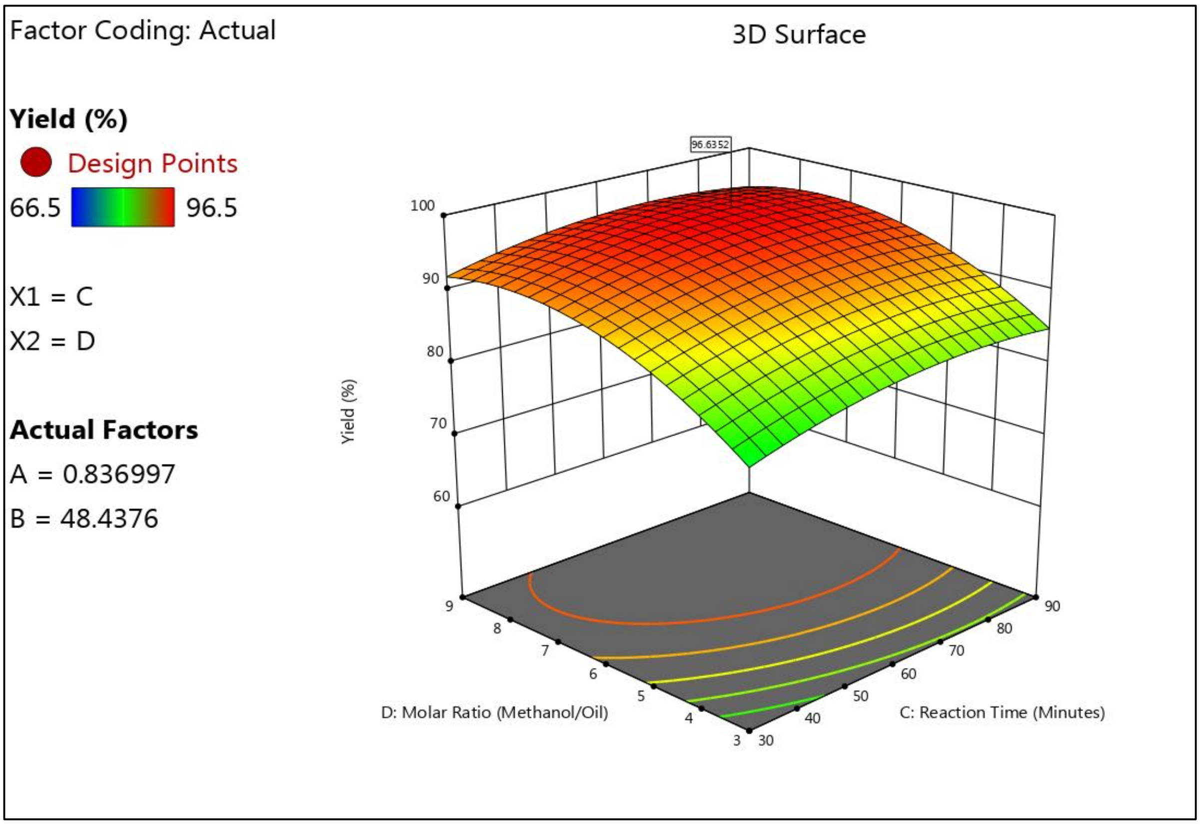


Figure 4.18: Effect of molar ratio and reaction time

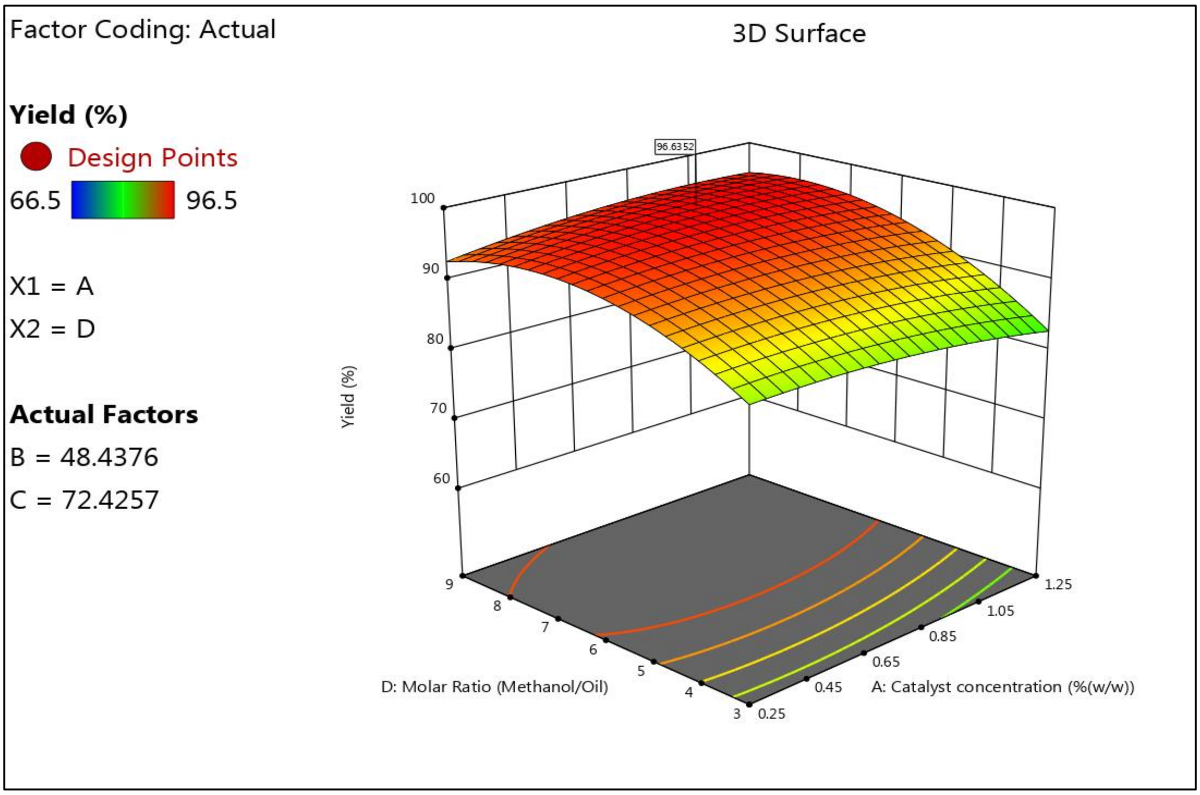


Figure 4.19: Effect of molar ratio and catalyst concentration

The interaction of various variables in three-dimension representations in a combination of each other when the other two variables are fixed for the finest yield of biodiesel production for JCO is represented in figure 4.14 to figure 4.19. Figure 4.14 to 4.19 shows the relation between two different variables which affect the yield while the other two variables kept constant. The ramp function of the transesterification process conducted to produce biodiesel of JCO is presented in figure 4.20. Ramp function showed the range of all the variables in which the optimum value is highlighted through a point. This point of all the parameter was considered for optimum process biodiesel production. It was found that by taking CC of 0.836997, RT of 48.4376°C, ToR of 72.4257 minutes, and MR of 7.61779 the yield of 96.6352% for biodiesel produced from jatropha oil can be achieved. However, those values were difficult to maintain therefore nearest whole number to the value was considered for the experiment. After the experiment, the yield of biodiesel prepared from jatropha oil was found near to 96.5 % only which again justified the significance of the model. The final experiment with the optimum value of all parameters was suggested by the design expert. According to optimising tool, the maximum yield of 96.64% can be possible but experimentally on these parameters the yield of 96.5% was achieved. The optimum value of all parameters is presented in table 4.9.

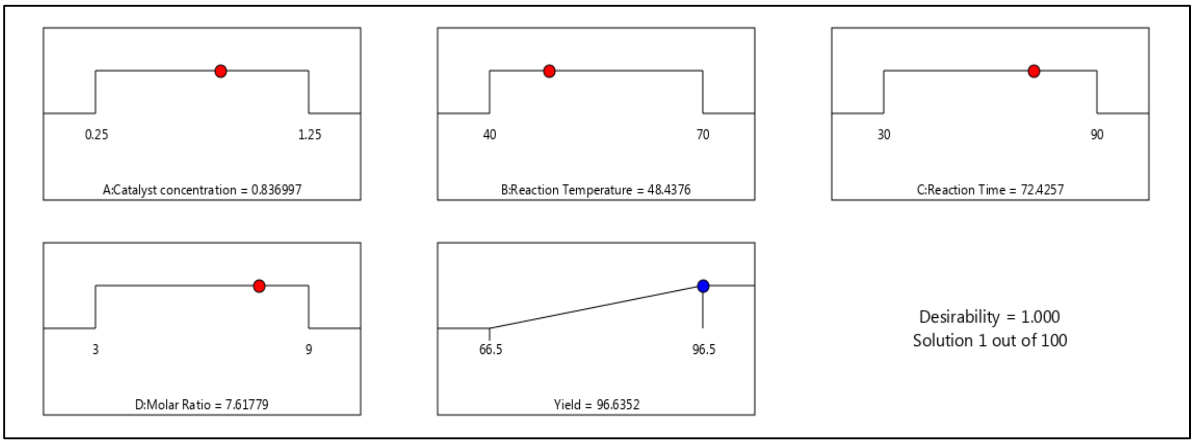


Figure 4.20: Ramp function of the esterification process

Table 4.9: Optimised process parameters for transesterification

Response	Optimized value of input process parameters				Predicted value	Experimental value
	A	B	C	D		
Yield (%)	0.8369	48.437	72.425	7.617	96.635	96.5

4.4. Preparation of Test Fuels

After the preparation of biodiesel from jatropha oil, some physicochemical properties were tested (detailed information about these properties is given in the next section) and found that some properties like density, the kinematic viscosity of jatropha oil methyl ester (JOME) were not desirable for a diesel engine. Therefore, neat JOME is utilised as fuel for an unchanged diesel engine to create cooking in injecter due to high viscosity and density. So JOME needed to mix with lower density and kinematic viscosity fuel to make its properties suitable for the conventional diesel engine. In this regards two different alcohols i.e. n-butanol and n-octanol were selected to prepare the blends of JOME. After that JOME was mixed with n-butanol and n-octanol in different ratios and the various blend of JOME were prepared. The nomenclature of all tested fuels is given in table 4.10. After preparation of blend, the physicochemical possessions of all tested fuels measured which is discussed in the next section in detail. The performance of these tested fuels was also used on unmodified diesel engine and detailed results with discussion are presented in this chapter only.

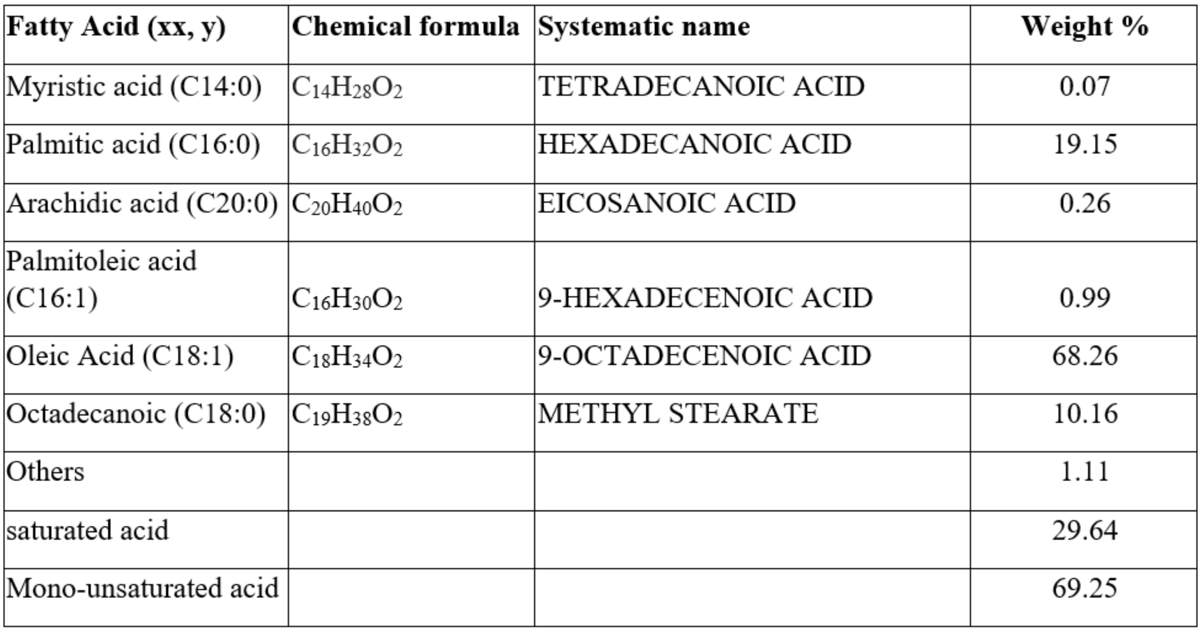
4.5. Physicochemical Properties

The tested fuels prepared in such a way that these can use as fuel in an unmodified diesel engine. After preparation, the important physicochemical properties of tested fuel like density, kinematic viscosity, flash point, calorific value, and cetane index of all tested fuels were measured as per ASTM standard which is already explained during chapter 3.

4.5.1. Fatty Acid configuration of JOME

To identify the fatty acid composition of JOME in this research GC-MS analysis was carried out. Which is depicted in table .4.10 and fatty acid profile in figure 4.21.

Table 4.10: Faty acid configuration of JOME.



Fatty Acid (xx, y)	Chemical formula	Systematic name	Weight %
Myristic acid (C14:0)	$C_{14}H_{28}O_2$	TETRADECANOIC ACID	0.07
Palmitic acid (C16:0)	$C_{16}H_{32}O_2$	HEXADECANOIC ACID	19.15
Arachidic acid (C20:0)	$C_{20}H_{40}O_2$	EICOSANOIC ACID	0.26
Palmitoleic acid (C16:1)	$C_{16}H_{30}O_2$	9-HEXADECENOIC ACID	0.99
Oleic Acid (C18:1)	$C_{18}H_{34}O_2$	9-OCTADECENOIC ACID	68.26
Octadecanoic (C18:0)	$C_{19}H_{38}O_2$	METHYL STEARATE	10.16
Others			1.11
saturated acid			29.64
Mono-unsaturated acid			69.25

The characteristics possessed by biodiesel subjected to the fatty acid composition of the methyl ester which is inherited from the feedstock. Fatty acid contemporaneous in JOME100 is in the range of 14-19 carbon atoms. One taster from prepared biodiesel is tested and outcomes display that it has 69.25% of unsaturated and 29.645% is saturated fatty acid. The presence of saturated acid components in biodiesel lowering the temperature of biodiesel as it has a very low burning temperature. The presence of an unsaturated component improves the heating value of methyl ester. Additionally, the combination of these two defines the characteristics of methyl ester [272], [273].

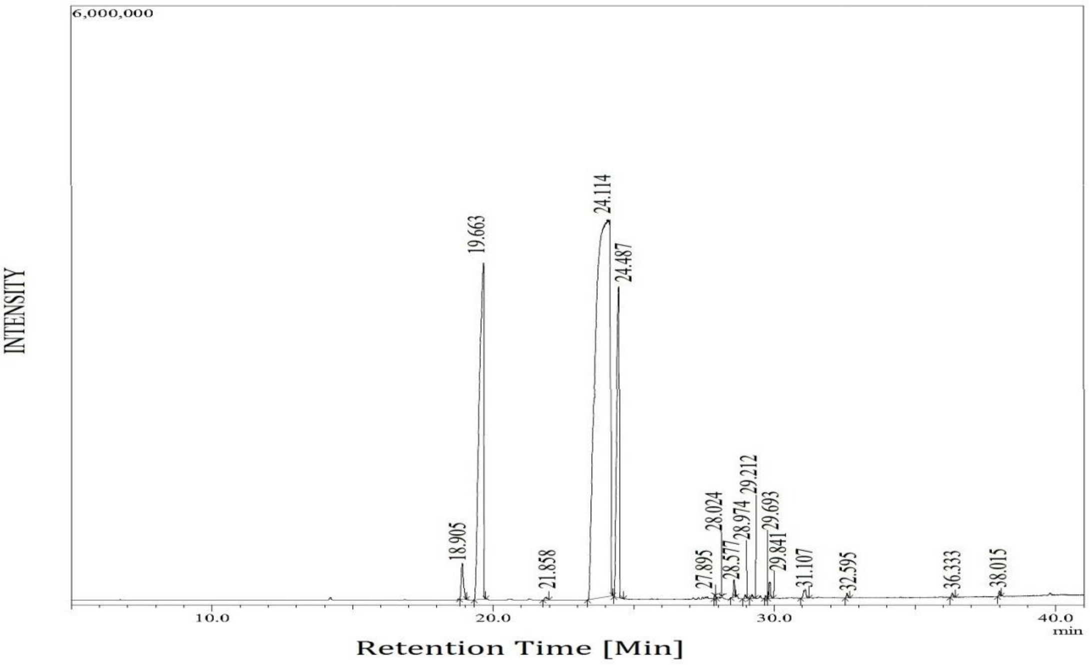


Figure 4.21: Fatty acid profile of JOME by Gas Chromatography

4.5.2 Density

The density is very important parameters for fuel when it is utilized in the IC engine. Liquid fuel is the main source of energy in that scenario, the density of fuel becomes very crucial property in the selection of fuel. The liquid fuels are generally sold in litre in that factor if the calorific value of liquid fuel is less that can be compensated with a higher density of the fuel. The same thing happens with biodiesel. The higher density of JOME similitude to mineral diesel which brings biodiesel at the comparable value of energy release per unit litre of fuel. The density of all tested fuels was compared and analysis is represented in figure 4.22. The density of all the tested fuels was measured as per the ASTM D 941 standard which is already explained in detail during chapter 3.

The density of biodiesel was found less as compare to its parent oil/ fat as density decreases during the transesterification process. In the present study biodiesel and alcohol are used for blending. It was observed that JOME has the highest density among all the tested fuels. The density of JOME was 872.27 kg/m^3 after JOME the density of n-octanol was highest among parent fuel which was 827.29 kg/m^3. The density of mineral diesel and butanol was 823.14 kg/m^3 and 807.58 kg/m^3 respectively. The density of other tested fuels laid in between. The density of JOME90B10, JOME80B20, JOME90O10 and JOME80O20 was 864.55 kg/m^3, 858.33 kg/m^3, 866.27 kg/m^3, and 862.64 kg/m^3 respectively.

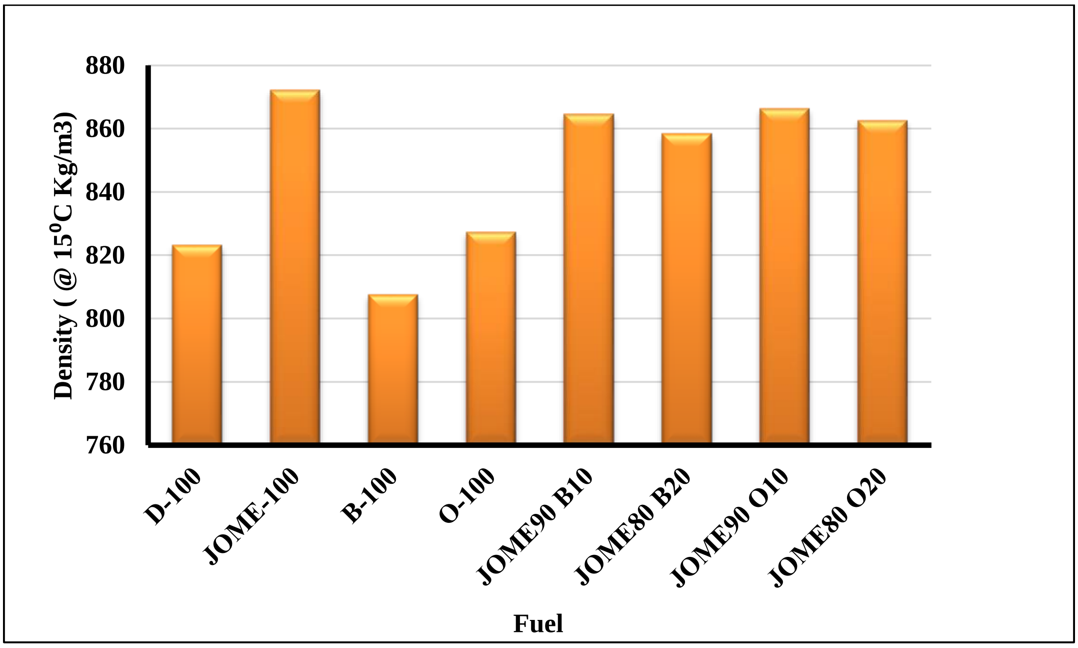


Figure 4.22: Density of all tested fuels

4.5.3. Kinematic viscosity

Kinematic viscosity is again one of the vital properties of fuel as it directly affects fuel delivery-components inclusive fuel pump, fuel injector, and fuel atomisation as these are the function of the viscosity of the fuel. For liquid, the kinematic viscosity increases with decreasing temperature. Therefore the kinematic viscosity becomes very crucial at a lower temperature. The higher viscosity leads to poor atomisation of fuel which is the main reason for soot emissions. Poor atomization also leads to higher CO & HC emissions which decline BTE of the engine.

The viscosity of vegetable oils and waste fats is very high as compared to petroleum diesel fuel which is the main obstacle in the utilising straight vegetal oil as fuel. Kinematic viscosity (KV) of vegetable oil and waste fat can be decreased with several methods which are already discussed in chapter 3. The effective method of decreasing the viscosity of oil and fat is the transesterification process or converting vegetable oil and waste fat into biodiesel. However, the density of most of the biodiesels has higher compare to petrodiesel. Therefore, blends of JOME were prepared with n-butanol and n-octanol. The viscosity of n-butanol was comparable to mineral diesel but the viscosity of n-octanol was found near to biodiesel. The kinematic viscosity of all tested fuels is compared in figure 4.23.

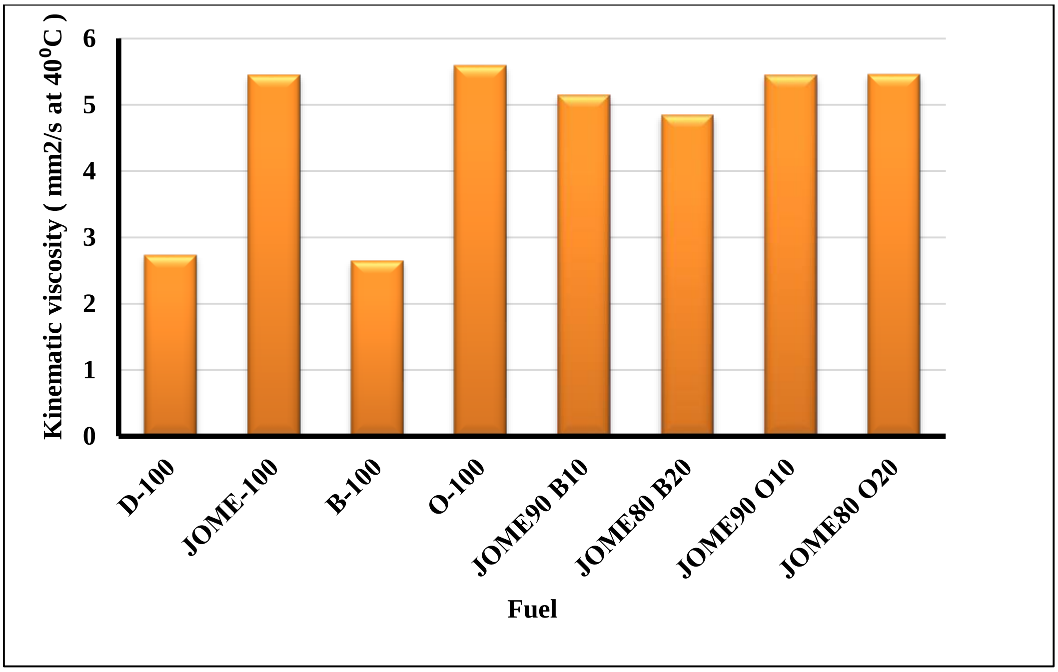


Figure 4.23: Kinematic viscosity of all tested fuels.

JOME has the highest KV among all parent fuels besides. The kinematic viscosity of JOME was 5.451 mm^2/sec which was much higher than mineral diesel which has a kinematic viscosity of 2.73mm^2/sec but it was still under the limit as per ASTM D6751. KV of n-butanol &n-octanol was 2.65 mm^2/sec &5.59 mm^2/sec correspondingly. The KV of JOME &n-butanol blends diminutions with upspring n-butanol percentage in the mixture. The kinematic viscosity of JOME90B10 & JOME80B20 was 5.15 mm^2/sec and 4.85 mm^2/sec respectively. Moreover, the kinematic viscosity of JOME90O10 and JOME80O20 is 5.445 mm^2/sec and 5.458 mm^2/sec respectively which shows that with the further addition of n-octanol in the mixture does not affect KV as JOME and octanol has a similar value of kinematic viscosity.

4.5.4. Calorific value

The calorific value (CV) of all tested fuels is restrained as per the ASTM D 240 standard. There is no limit of calorific value for biodiesel as per the ASTM D 6751 standard. But it is a very significant property of fuel, especially when utilised in IC engines. The CV represents the quantity of heat energy released by fuel while it goes for complete combustion. Usually, the calorific value of all vegetable oils, waste fats, and biodiesel prepared from them has lower calorific value as compared to petroleum diesel as these all contain free oxygen with them. Similar to vegetable oils and biodiesel, the alcohols are also contained oxygen therefore the calorific value of most of the alcohols is less as compared to petrodiesel. However, the CV of alcohol increases with an increase in carbon content because it leads to a decrease in the oxygen percentage in alcohol.

The CV of all test fuels is compared in figure 4.24. From data, the CV of n-butanol is found lowest among all test fuels. The CV of n-butanol was 33.5MJ/kg, the lower CV of n-butanol is owing to higher oxygen content which is 21.6% in n-butanol. The petrodiesel has an uppermost CV of 45.52 MJ/kg where the JOME &n-octanol has a calorific value of 40.89 MJ/kg & 38.48 MJ/kg correspondingly. The CV of other test fuels JOME90B10, JOME80B20, JOME90O10, and JOME80O20 was 40.055 MJ/kg, 39.12 MJ/kg, 40.54 MJ/kg, & 40.308 MJ/kg respectively.

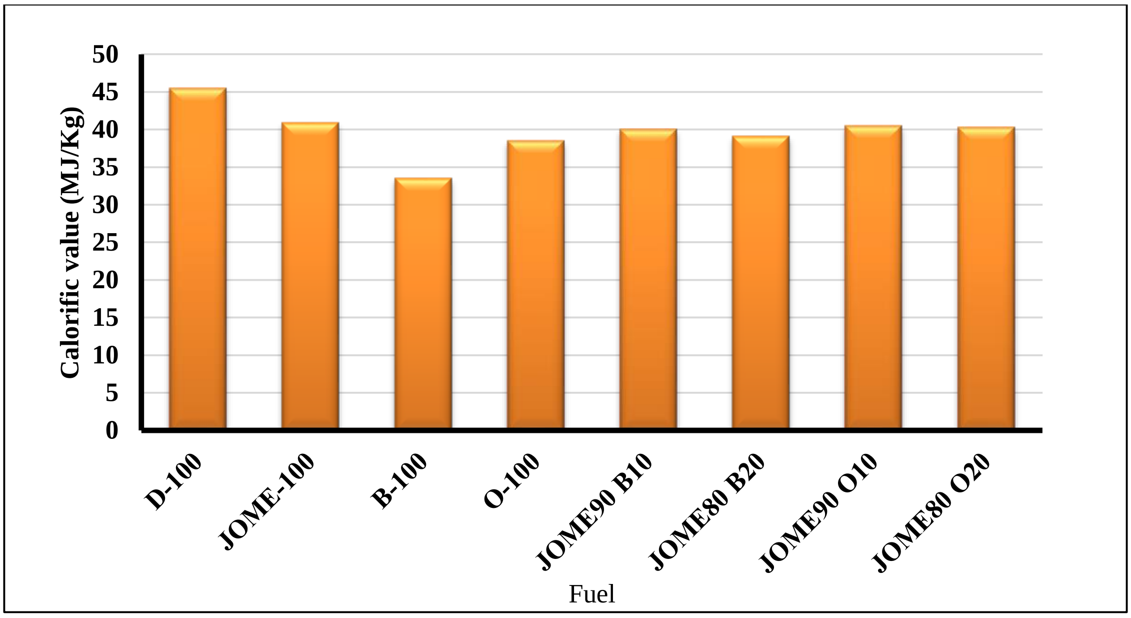


Figure 4.24: Calorific value of all test fuels

4.5.5. Cetane index

Cetane index is an approximation measurement of cetane number which represents the combustion quality of liquid fuel when it ignites automatically due to higher temperature and higher pressure in the compression ignition engine. The cetane number is measured by continuously variable compression ratio cooperative fuel research (CFR) cetane engine as per the ASTM D613 standard. The availability of this engine is very limited therefore to resolve problems two different methods are used to determine the cetane index which gives an approximate value of cetane number. These two methods are two variable methods and four variable methods. As discussed in chapter 3, the four variable methods are more efficient and give a very approximate value of the cetane index as compare to two variable methods. The cetane index of all test fuel is measured as per ASTM D4737 standard which is already explained during chapter 3.

The cetane index of JOME was 51 which is highest among all test fuels. The similitude of the cetane index of all tested fuel is given in figure 4.25. The cetane index of n-butanol was17 which was lowest among all the test fuels. Cetane index of other parent fuel i.e. petroleum diesel and n-octanol is 48 and 39 respectively which laid between JOME and n-butanol. The blends contain n-butanol i.e. JOME90B10 and JOME80B20 has a lower cetane index of 47 and 44 respectively. It was found that increasing n-butanol content in blend pointers to the diminution in the cetane index. Furthermore, the cetane index of n-octanol was comparable to petrodiesel so increasing the content of n-octanol in bled does not affect the cetane index with that rate. The cetane index of JOME90O10 and JOME80O20 was 49 and 48 respectively.

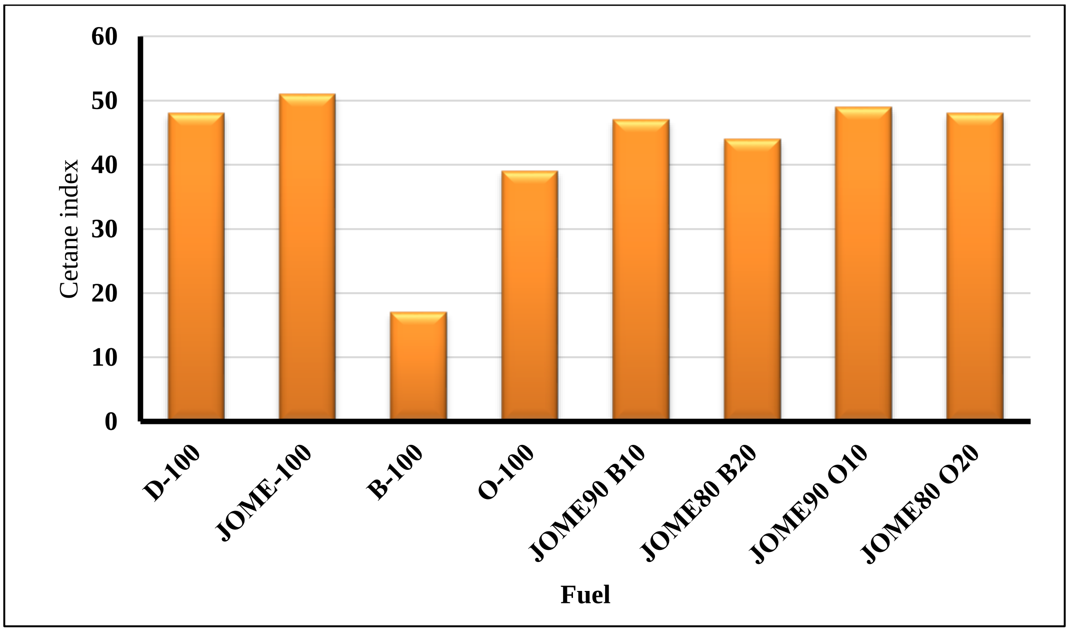


Figure 4.25: Cetane index of all test fuels.

4.5.6 Flash point

It is considered a crucial property for the safe handling of fuel at high ambient temperature. The flash point is delineated as the lowest temperature at which fuel must be heated to release adequate vapour to start auto ignite in the presence of air and external heat source of ignition such as flame or spark. The measurement of the flash point of fuel explains in chapter 3. The flashpoint of biodiesel and n-octanol is an upmost similitude to petrodiesel but n-butanol has a lower flash point 32 ^{0}C than diesel 61^{0}C.However, the mixture of n-butanol/n-octanol &biodiesel has a higher flash point than diesel. Flash point of other test fuels JOME90B10, JOME80B20, JOME90O10, and JOME80O20 were 156^{0}C, 142^{0}C, 16^{0}C, and 152 ^{0}C respectivelyaredepicted in figure 4.26.

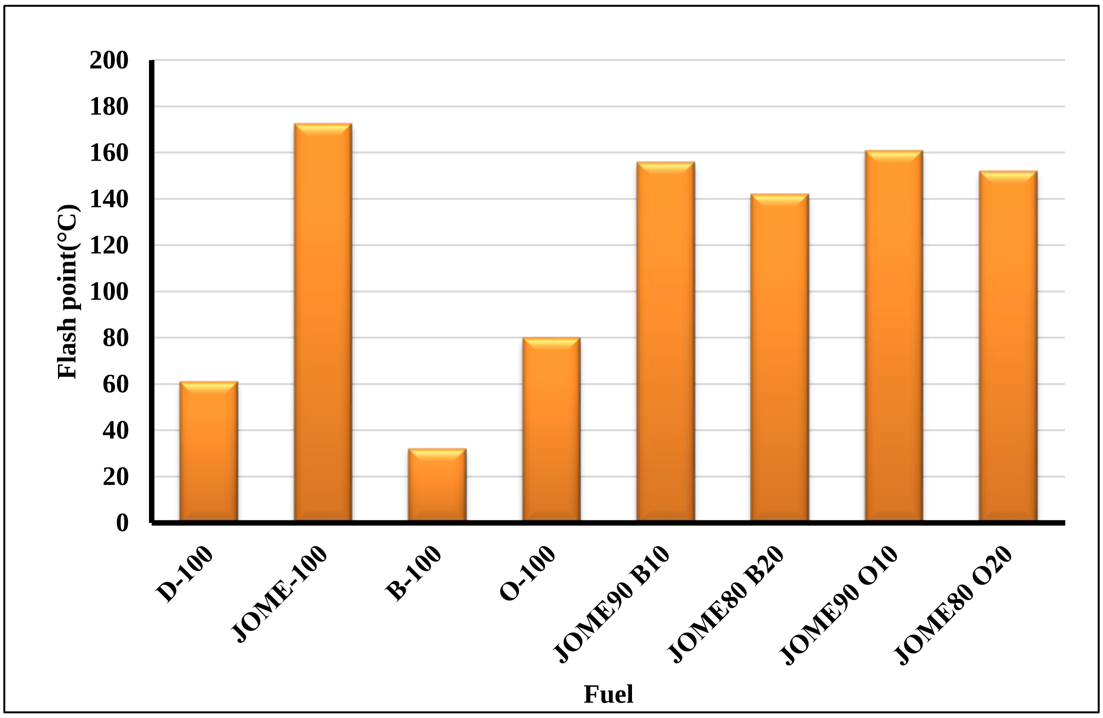
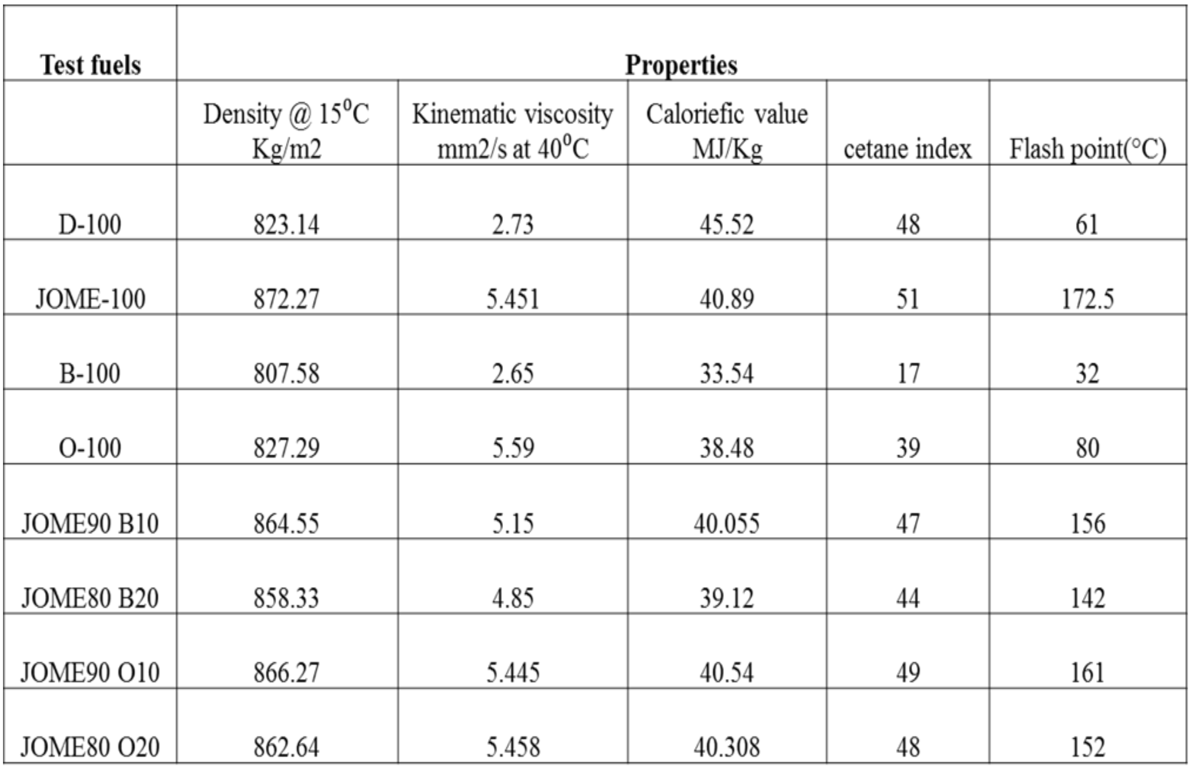


Figure 4.26: Flash point of all test fuels

All the properties measured and mentioned above are present in table 4.11.

Table 4.11: Physicochemical properties of all test fuels



Test fuels	Properties				
	Density @ 15^{0}C Kg/m2	Kinematic viscosity mm2/s at 40^{0}C	Caloriefic value MJ/Kg	cetane index	Flash point(°C)
D-100	823.14	2.73	45.52	48	61
JOME-100	872.27	5.451	40.89	51	172.5
B-100	807.58	2.65	33.54	17	32
O-100	827.29	5.59	38.48	39	80
JOME90 B10	864.55	5.15	40.055	47	156
JOME80 B20	858.33	4.85	39.12	44	142
JOME90 O10	866.27	5.445	40.54	49	161
JOME80 O20	862.64	5.458	40.308	48	152

4.5.7 Change in properties of blend with time

The biodiesel has low oxidation stability than mineral diesel. The fuels were stored for one year in a tightening glass container. The properties like density, Kinematic viscosity, and calorific value have been measured after every month and it was observed that all properties varying with time. However density, kinematic viscosity was marginally increased while calorific value was slightly decreased with time as shown in Figure 4.27, 4.28, and 4.29.

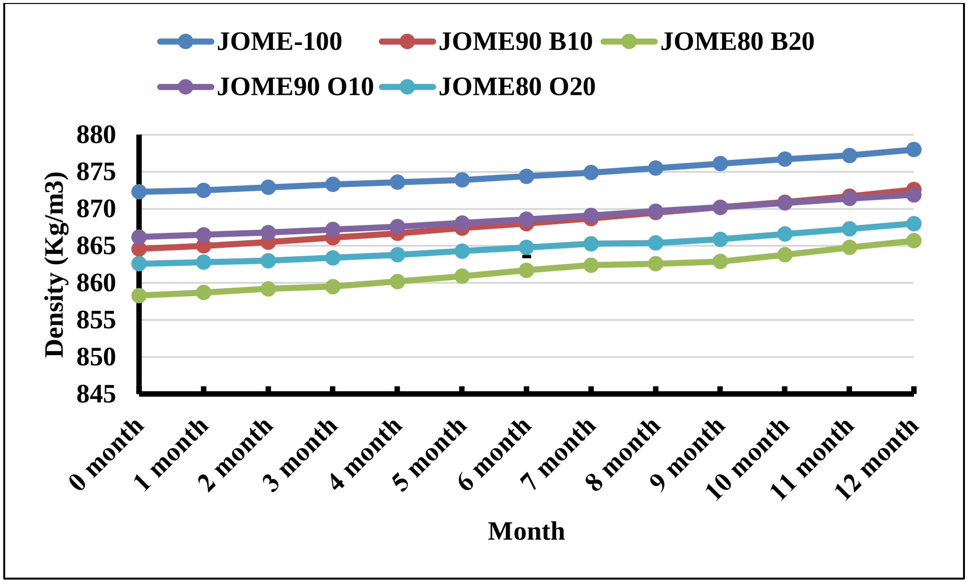


Figure 4.27: Change in density with time

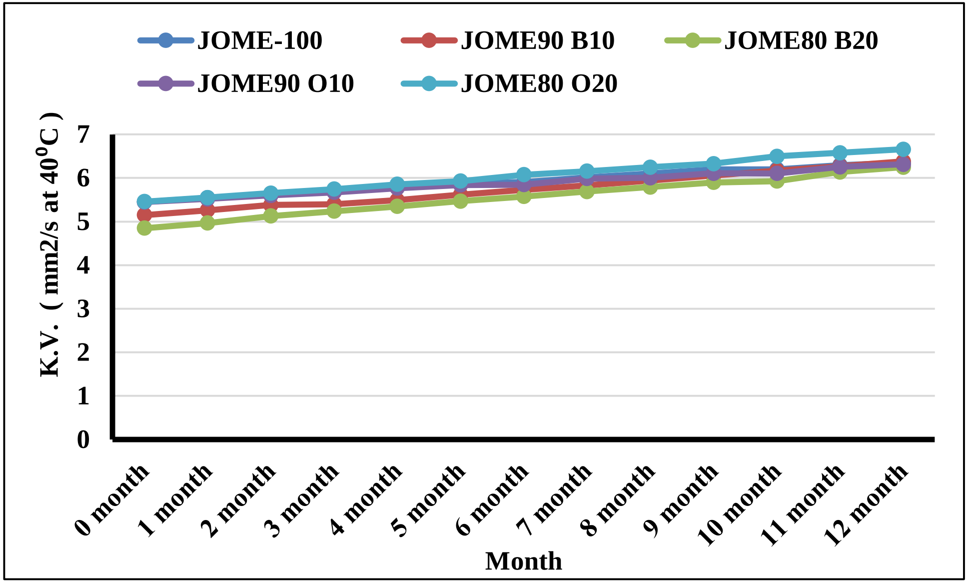


Figure 4.28: Change in kinetic viscosity with time

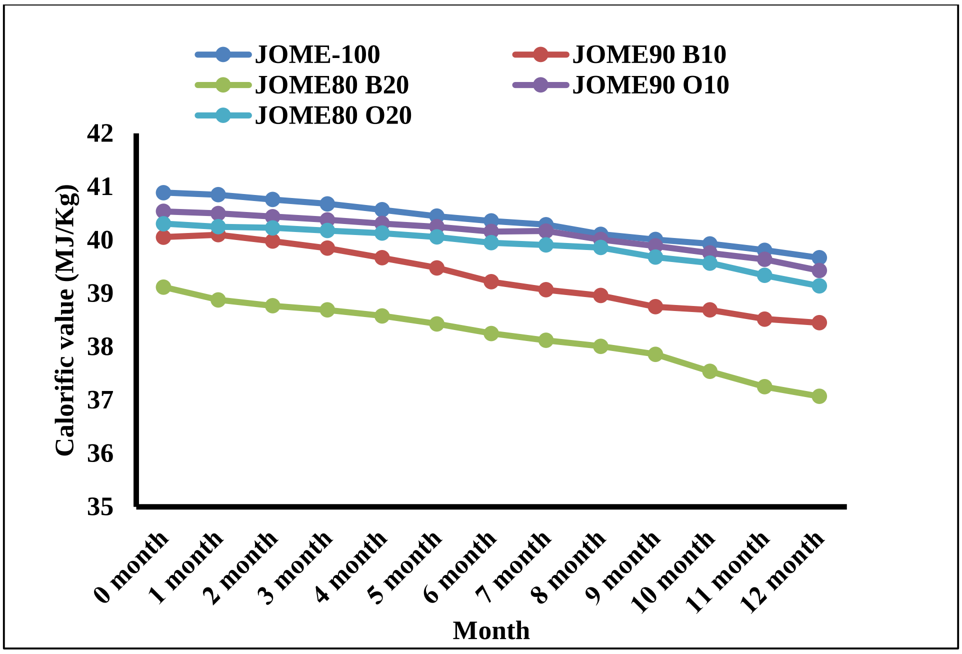


Figure 4.29: Change in calorific value with time

4.6 Engine Performance

The performance of unmodified direct injection, constant speed, and the stationary engine was analysed in this section when the engine was running of all tested fuels i.e. JOME, JOME90B10, JOME80B20, JOME90O10, and JOME80O20. The results obtained during the experimental investigation were compared with conventional diesel. The execution such as BTE, BSEC are measured during the present session. The engine was operated with a fixed rotation of 1500rpm for all loading conditions. The engine was running with a load variation of 20%, 40%, 60%, 80%, and 100% for all tested fuel during the present research.

4.6.1 Brake Thermal Efficiency

The brake thermal efficiency in short BTE is a fraction of mechanical energy produced per second on the brake drum of the engine to the total chemical energy supplied to produce that power. The BTE is also known for fuel conversion efficiency. The power generated on the brake drum of the engine is usually measured with various types of dynamometers. In the present steady an eddy current dynamometer was used that was directly coupled with prime mover shaft. The load was applied to the engine with the help of that dynamometer only. The effect of the blending of n-butanol and n-octanol with JOME in different proportions of 10% & 20% on the performance of the engine was measured and analysed in this section. The consequences acquired were similitude with baseline data.

The variation in BTE of an engine with respect to different loading conditions is represented in figure 4.30.1. Generally, BTE of an engine was increasing with load up to higher loading conditions (higher loading condition was assumed to be 80 to 90% of full load) due to increasing brake power. Other reasons for increasing BTE with load were increasing fuel content in A/F mixture, higher inside chamber pressure which causes sophisticated flame propagation speed and better combustion. Further increase in load, i.e. full load condition, steerage to the diminution in BTE of engine marginally. This occurs due to a richer fuel-air mixture which caused incomplete combustion and results in lower BTE [229].

All the test fuels attained the maximum BTE at a higher load range i.e. near to 80% of maximum load. The conventional diesel engine running on petroleum diesel showed the maximum BTE of 30.43% among all test fuels followed by JOME80O20, JOME90O10, JOME80B20, and JOME90B10 which has maximum BTE of 29.75%, 28.72%, 27.25%, and 25.85% respectively. The JOME has lowermost BTE amongst all test fuels which was25.14%. The lowest BTE of JOME among all test fuels was because of higher boiling point & KV of JOME along with lower calorific value which results in poor atomisation and which leads to poor combustion[274]. Also, the lower calorific value of JOME with the above reasons was responsible for poor BTE among all fuels.

The mixing of JOME along n-butanol & n-octanol improved the BTE of the engine. The CV & cetane number of n-octanol was superior to n-butanol, therefore, the blending of n-octanol with JOME improved the BTE as compare to JOME and n-butanol amalgams. Further, the kinematic viscosity of n-butanol was lower than JOME hence the blending of these alcohols with JOME improved the kinematic viscosity of blend. The increasing the content of n-octanol and n-butanol in the blend mend deflagration characteristics of fuel. The situation can visualise clearly from figure 4.30, the blending of n-octanol gave better results in improving BTE of JOME as compared to n-butanol. The reason for this is the higher cetane index of n-octanol which is 39 as compared to n-butanol which has a cetane index of 17 only. Also as discussed earlier the CV of n-octanol is higher relatively JOME & n-butanol which makes it a better component for blending. Similar kinds of results were observed by Yilmaz et al. [275] while use n-butanol and biodiesel blends in the diesel engine. Deep et al. [276] and Devarajan et al. [232] used octanol and biodiesel amalgam with their analyse enactment of the engine. The authors also find similar kind of results during their research. Figure 4.31and 4.32 shown the variation of BTE with respect to D100 and JOME100 respectively.

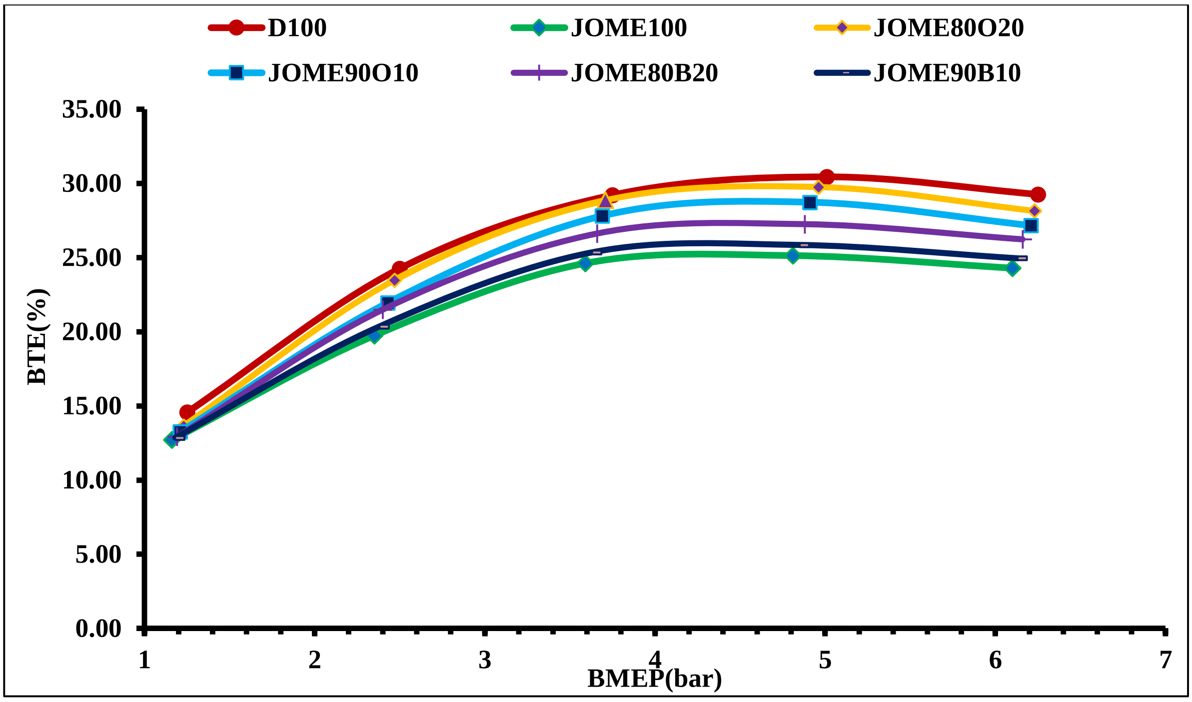


Figure 4.30: BTE vs. BMEP.

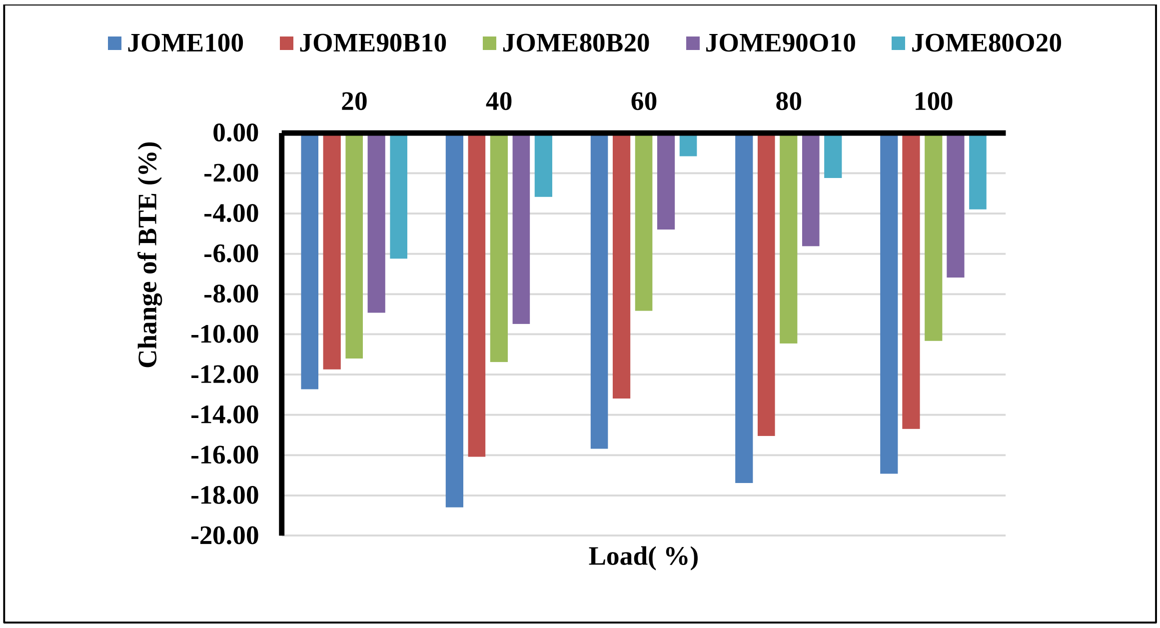


Figure 4.31: Variation of BTE compare to Diesel

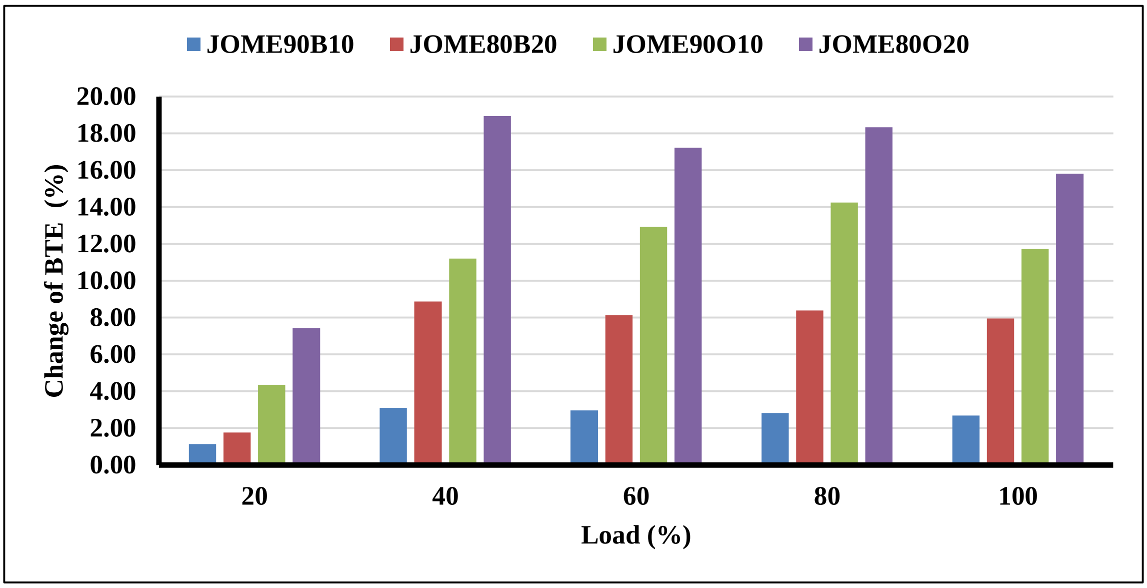


Figure 4.32: Variation of BTE compare to JOME100

4.6.2 Brake specific energy consumption

Brake specific energy consumption famously known with its short name of BSEC is the fraction of BP to the multiplication of mass stream proportion of fuel to generate that power with the calorific value of the fuel. In a simple statement, BSEC is the amount of energy utilised by the engine to produce one kilowatt of brake power. The BSEC during the present work is calculated with the formulas discussed in the last chapter of system development. One more similar parameter is measured by the number of researchers during analysing the performance of the engine that is known as brake specific fuel consumption (BSFC). The only difference between BSFC and BSEC is that BSEC is calculated by multiplying the BSFC with its calorific value. The BSEC is assumed to be a better parameter to compare the performance of the engine if two or more different fuels are used during the research. The BSEC gives them a common platform to analyse the performance of the engine. It has also become important as it uses two important parameters of the fuel i.e. mass flow rate which depends upon kinematic viscosity and density with calorific value. As discussed earlier, the density of biodiesel is higher as compared to mineral diesel while CV of biodiesel and n-butanol and n-octanol is much lower than mineral diesel hence the BSEC of all blend is higher than mineral diesel. The variation of BSEC of the engine while running on different fuels and different loading conditions is represented in figure 4.33.

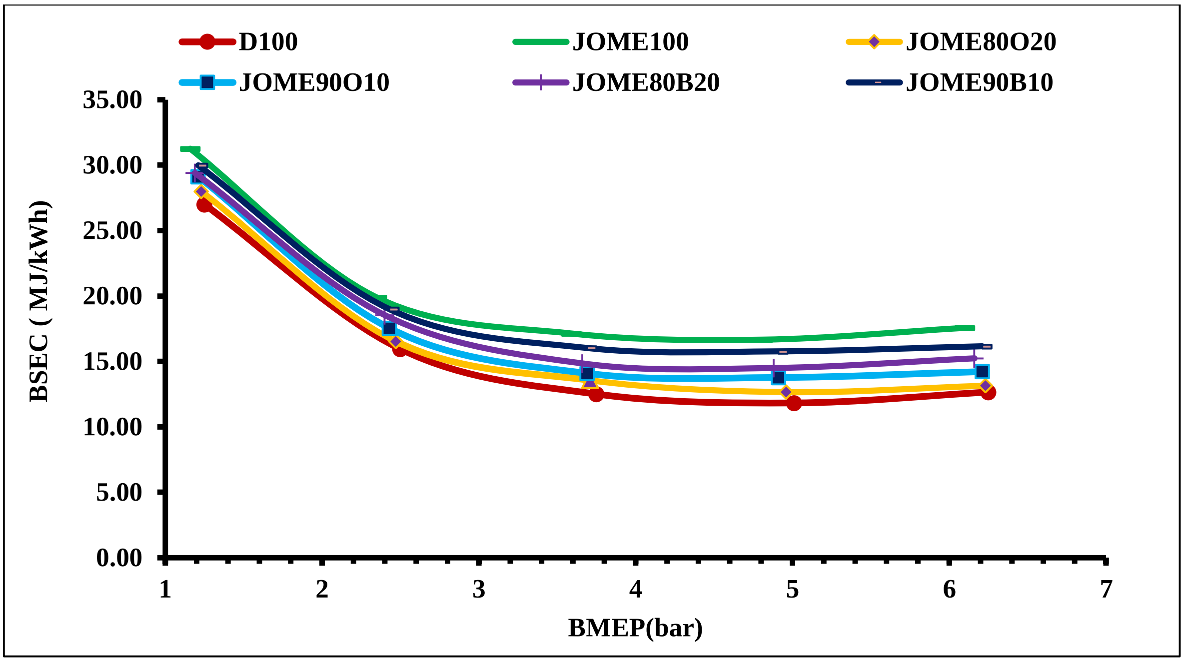


Figure 4.33: BSEC vs. BMEP.

The BSEC of the stationary engine using all test fuels JOME100, JOME90B10, JOME80B20, JOME90O10, and JOME80O20 were measured for all loading conditions, and the results were compared with a conventional diesel engine to analyse the effect of using different test fuels. As discussed in the earlier section of BTE, the highest BTE of the engine was achieved around 80% loading condition by all test fuels. Therefore, the engine also showed its lowest BSEC at that loading condition only as BTE and BSEC or BSFC are inversely proportional to each other. The changes in the variation of BSEC of blends with respect to D100 and JOME100 was depicted in percentages correspondingly in figure 4.34 and 4.35.

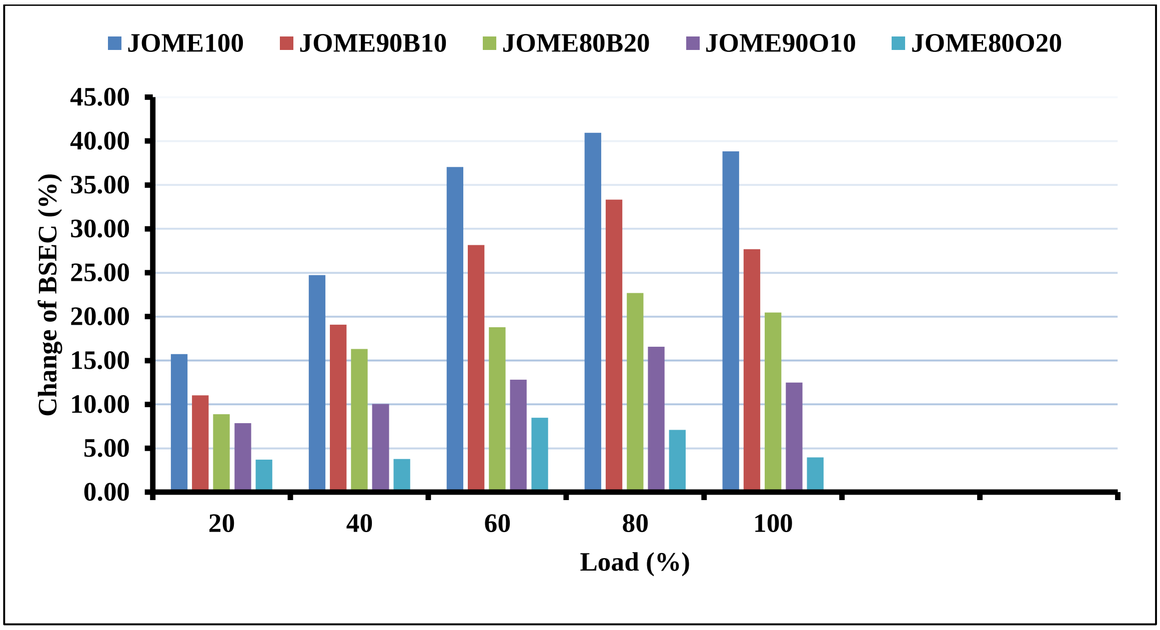


Figure 4.34: Variation of BSEC compare to Diesel

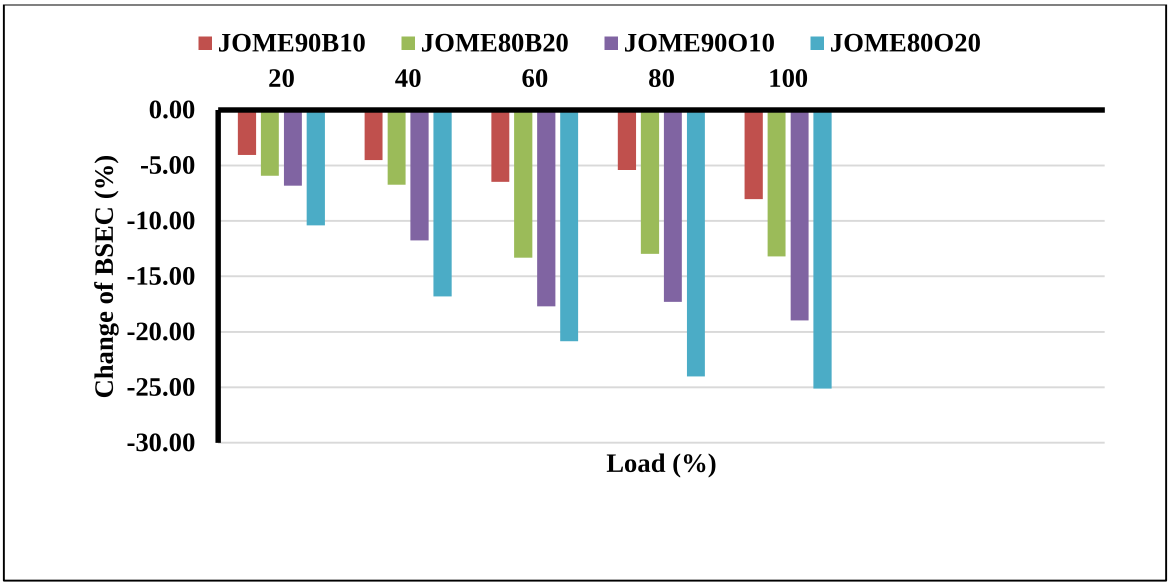


Figure 4.35: Variation of BSEC compare to JOME100

The BSEC of conventional diesel engines remained least among all test fuel for all loading conditions. On the other end, the BSEC of JOME100 was observed highest among all test fuels. The reverse trends were observed for BTE for all fuels. The BSEC of the mineral diesel engine was11.82 MJ/KWh which was least among all the test fuels at 80% loading conditions. The BSEC of other test fuels was 16.66 MJ/KWh, 15.76 MJ/KWh, 14.50 MJ/KWh, 13.78 MJ/KWh, and 12.66 MJ/KWh for JOME100, JOME90B10, JOME80B20, JOME90O10 and JOME80O20 respectively at 80% loading condition. The opposite trend was observed during the analysis of BTE of the engine.

It was perceived that BSEC of engine shrinkages with intensification in load and brake mean effective pressure (BMEP) for all test fuels. However, the line represents the BSEC of various fuels that are very close to each other at low load but with the upsurge in load & BMEP of the engine the difference between those curves increased which can be seen from figure 4.33 clearly. This was because at higher load the energy requirement increases which was fulfilled by supplying more fuel to the engine[274]. The fuel supply can be increase by increasing the

MFR of fuel to the engine. The calorific value of JOME, n-butanol, and n-octanol was less than mineral diesel fuel so that BSEC of all blend was more.

The BSEC of the engine further increases after 80% loading or at full load. The BSEC of the engine using JOME100, JOME90B10, JOME80B20, JOME90O10, & JOME80O20 as fuels at full load was 17.56 MJ/KWh, 16.15 MJ/KWh, 15.24 MJ/KWh, 14.23 MJ/KWh, & 13.15 MJ/KWh individually. However, mineral diesel showed the lowest BSEC among all test fuel. The BSEC of conventional diesel at full load was 12.65 MJ/KWh which was much less than other tested fuels. The reason was similar to higher BTE. The mineral diesel has a higher CV and lower density and kinematic viscosity which it to combust in a better way in the combustion chamber [277]. However, the slop of the BSEC curve for mineral diesel increases at a faster rate at full load as compared to other test fuels. This was because all other test fuel has contained some free oxygen which makes them better fuel, especially for higher loading conditions.

The increasing percentage of n-butanol& n-octanol in mixtures resulted in lowering BSEC of the engine. This occurred because n-butanol & n-octanol has better kinematic viscosity and flash point as compare to neat JOME. Therefore increasing the percentage of better properties fuel in blend increased the overall properties of the blend. The blending of n-octanol with JOME gave better results similitude to the blending of n-butanol with JOME. The foremost reason was the higher calorific value and cetane index due to this n-octanol act as better fuel than n-butanol. Mixing of n-butanol & n-octanol with JOME also rallies atomisation physiognomies of fuel which improve the atomisation characteristic of fuel and led to improving BSEC of the engine. Similar kinds of results are also acquired by Yilmaz et al. [275] and Nanthagopal et al. [278]. Therefore it may be concluded that up to 20% blending of n-butanol and n-octanol by capacity portion in JOME at the foremost throat to improvement in BSEC of the engine.

4.7 Emissions characteristics

The exhaust outcomes components of DI stationary diesel engines are analysed in this section. The exhaust emissions like CO, NO_X, HC & smoke opacity of diesel engines measured for all the test fuels, and the result is compared with baseline data. Similar to performance characteristics of the engine, emissions are also measured at various loading conditions like no load, 20%, 40%, 60%, 80%, and full load conditions.

4.7.1 CO Emission

The carbon monoxide (CO) emission in any internal combustion engine represents the incomplete combustion of fuel because of insufficient availability of oxygen in the inside of the cylinder. However, CO emission in the CI engine depends upon some other factors as well as the richer fuel-air zone. This can occur only in the compression ignition engine as only air is suppressed through compression stroke & fuel is injected during the end of compression stroke which may cause a local richer fuel air zone within the combustion chamber. This is not the case in SI engines as consistent A/F assortment is sent to inside of cylinder during intake stroke so there is not a probability of creation of a local richer fuel air zone in the cylinder. Another reason for CO emission in the compression ignition engine is lower wall temperature during the starting period when the engine just starts. The CO emission of the diesel engines reduced through innumerable approaches alike increasing the temperature of inlet air, increase the oxygen availability in the cylinder which helps in comprehensive incineration of fuel. In this regard, the blending of alcohol and biodiesel with petroleum diesel is found very effective for CO emission reduction and this method is used by various researchers [209], [254], [279].

The poor spraying characteristics of the injector also can be the main reason for higher CO emission as it encourages the formation of local richer fuel air zones. The CO emission of the engine was measured with the help of di-gas analyser which is already explained in chapter 3. The CO emission was measured in the percentage of the total exhaust coming out from the engine in this study. The variation of CO emission in the exhaust of the engine while operating on test blend at different loading conditions and comparison with baseline data is presented in figure 4.36. Usual trace of CO emissions fora normal diesel engine was that the CO emissions decrease slightly from no load to intermediate loading situation & after that, it increases at a faster rate with the load. The highest CO emissions in a diesel engine were noticed at the full load condition. A similar trend was followed by other test fuels as well. The variation in CO emissions for various test fuel was negligible up to intermediate loading condition. However, after the BMEP of 3 bar the variation was visible in the graph and at full load large difference can be observed among all test fuels.

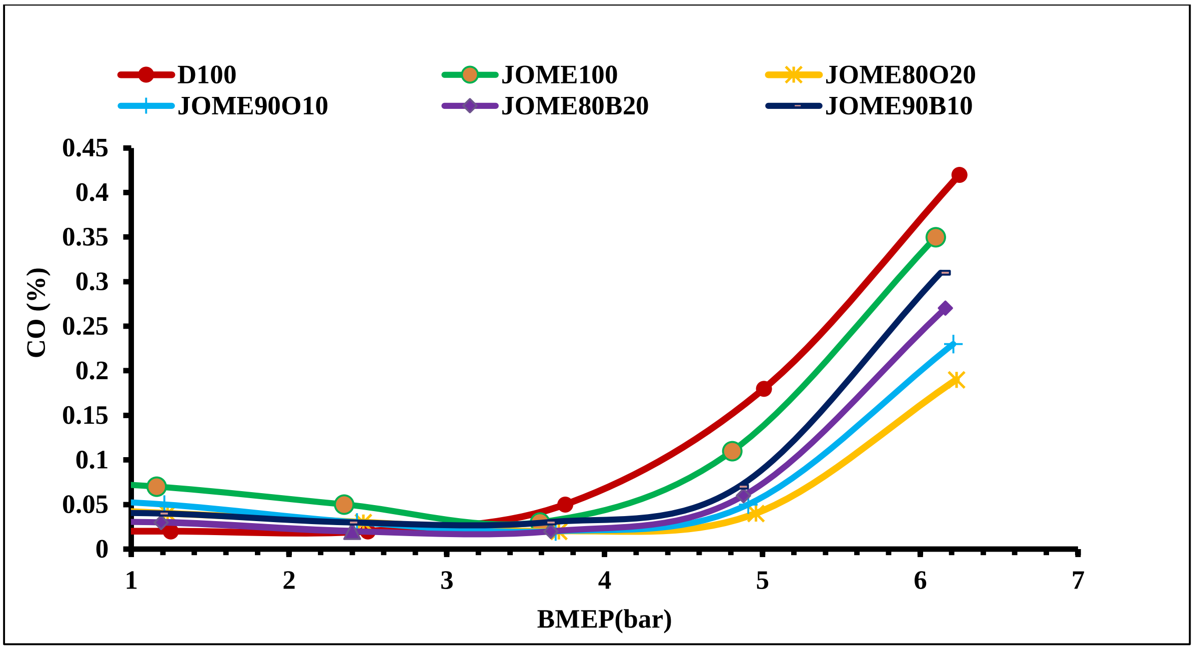


Figure 4.36: CO emissions vs. BMEP

The CO release for petrodiesel was noticed minimal similitude to other test fuels at lower load however this difference was very less and to be neglected as discussed earlier in this section. The higher CO emission for other test fuels was due to their higher kinematic viscosity which leads to improper atomisation and finally ends with incomplete combustion. This incomplete combustion of JOME results in higher CO emissions at lower load [85]. At higher and full load conditions, the JOME, n-octanol, and JOME, n-butanol blend were performing well as compared to mineral diesel fuel and JOME100. At full load, JOME80O20 causes the least CO release as compared to other test fuels. The CO emission for JOME80O20 was 0.19% where other test fuels i.e. JOME90O10, JOME80B20, JOME90B10 and JOME100 has CO emissions of 0.23%, 0.27%, 0.31% and 0.35% respectively. On the other hand, the CO emission of mineral diesel was found 0.42% at full load which was much higher than other test fuels. If the CO emissions of JOME80O20 and JOME90O10 was compared with CO emissions of mineral diesel, the mineral diesel was emitted approximately two times CO compared to JOME80O20 and JOME90O10. The variation of CO emission in percentage with comparison to D100 and JOME100 is depicted respectively in figure 4.37 and 4.38.

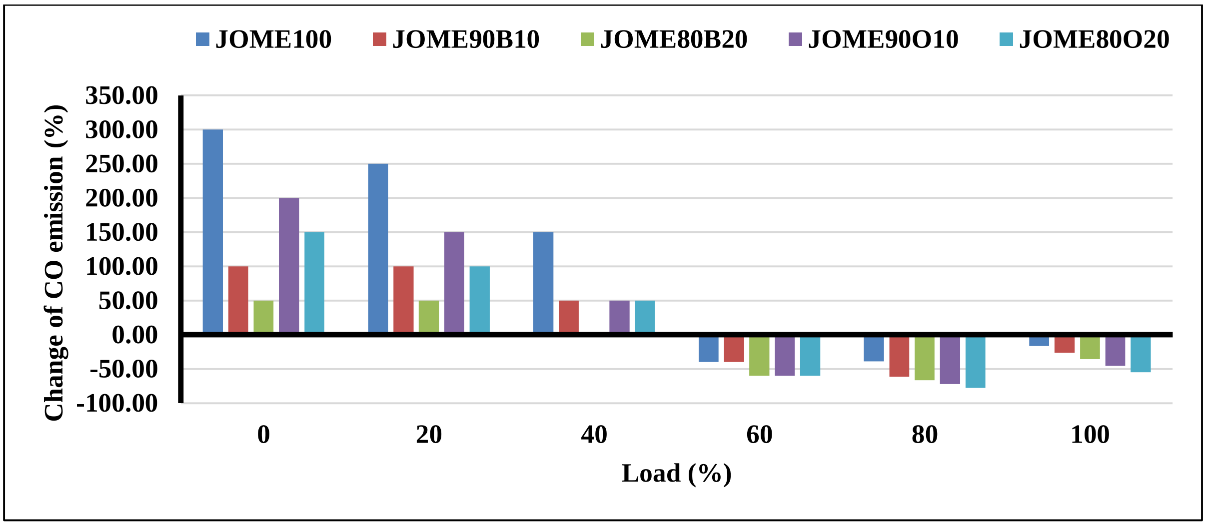


Figure 4.37: Variation of CO emission compare to D100

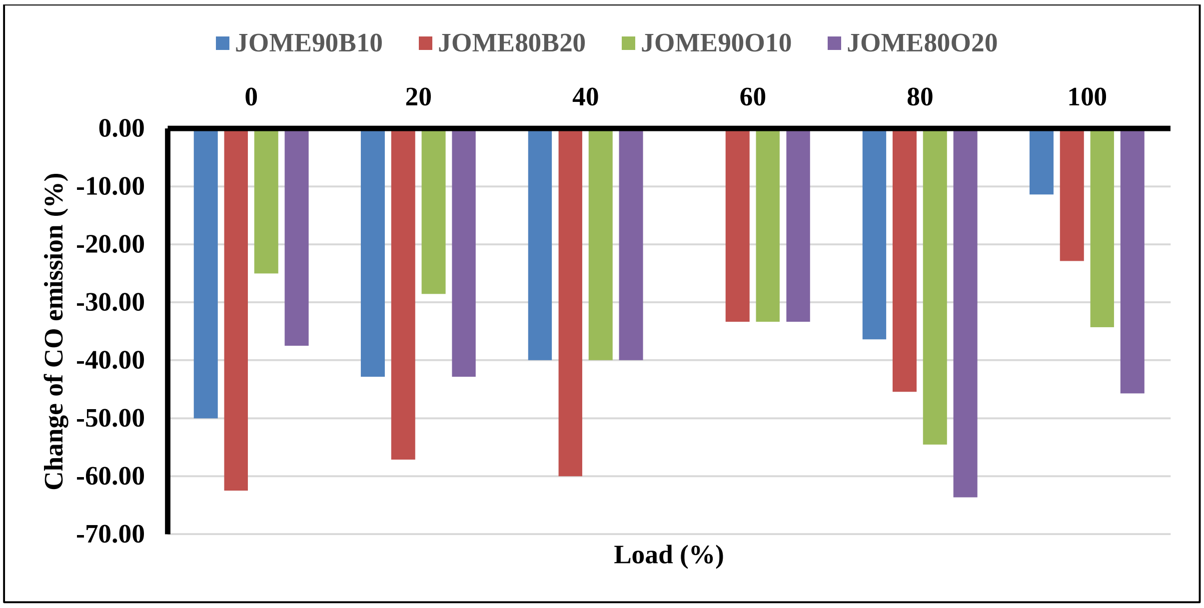


Figure 4.38: Variation of CO emission compare to JOME100

The reason for less CO emissions of biodiesel and alcohol blends is the presence of free oxygen in it. However, more oxygen is present inside of the cylinder to complete the oxidation of fuel. Due to the richer F/A ratio inside of the cylinder cause deficiency of oxygen available for the combustion, this contributes to incomplete incineration of fuel and CO emissions upsurges. Mineral diesel fuel does not have free oxygen in it which indications of developed CO emissions. On the other hand, JOME, n-butanol & n-octanol have free oxygen which makes the combustion smoother at a higher load where richer F/A mixture present in the inside of the cylinder. This free oxygen is the frontrunner toward completing the combustion and results in lower CO emissions. Figure 4.36 shows that JOME mixture with n-octanol produces less CO emissions similitude to JOME and n-butanol blends. This trend due to a higher cetane index of n-octanol over n-butanol & lower latent heat of vaporisation (LHV) of n-octanol compared to n-butanol.

4.7.2. NO_X Emissions

The NO_X emissions contain various types of oxides of nitrogen but the main contribution is by nitric oxide (NO) and nitrogen dioxide (NO_2) only. Generally, nitrogen as is inert in nature but at the higher temperature, the reactivity of nitrogen increase and it start to react with oxygen present in inside of the cylinder. The NO_X formation occurs in three ways in the combustion chamber which are: fuel NO_X, thermal NO_X, and prompt NO_X. The NO_X formation mechanism is also known as Zeldovich Mechanism. The name of the mechanism is given after the name of Russian scientist Y. B. Zeldovich introduces this mechanism the first time in 1947. The Y.B. Zeldovich dictates that the NO_X formation depends upon the amount of excess oxygen present in the combustion chamber, the temperature of the burnt gases, and the most important is the local fuel-air ratio.

The thermal NO_X is formed in the combustion chamber (CC) while nitrogen is reacted with the excess oxygen contemporary in CC at a higher temperature which is released due to the combustion of fuel. The thermal energy is used during this process to form NO_X that's why it is known as thermal NO_X. The thermal NO_X production in the cylinder depends upon the time for which the burnt gas remains in the cylinder after combustion and ignition delay time of fuel. The nitrogen present in the two forms in the engine cylinder is the content of nitrogen available in the fuel which is in very less quantity. The second is the atmospheric nitrogen enters into CC in the form of air which contains nearly 79% of air by volume.

The temperature & pressure in chamber upsurges with enhancement in load. Higher temperature and pressure are desirable conditions for NO_X formation. Therefore, the NO_X release of the engine developed with a rise in load & speed of the engine [280]. In the present study, the constant speed diesel engine was used therefore the NO_X emissions were analysed w.r.t. load and BMEP of the engine. The variation in NO_X exhausts of engine operative on different test fuel at different loading conditions is portrayed in figure 4.39. As discussed earlier the increasing engine load the NO_X emissions also increase and the same trend was observed in the present study for all test fuels. However, the use of JOME, n-butanol & n-octanol, upsurges NO_X formation henceforward consequences in higher NO_X outage. NO_X emissions of an unmodified engine using petrodiesel are least among all test fuels throughout the loading.

The NO_X formation curve showed an almost linear relationship with the engine load and BMEP. The NO_X emissions of JOME100 was highest amongst tested fuels at full throttle positions. The reason is the availability of oxygen in the fuel which supplies the excess oxygen to the nitrogen and results in the NO_X formation. Also higher cetane index indications of increased incineration duration of the fuel which provide more time for a suitable environment of NO_X formation inside the combustion chamber. However, the mixing of JOME along n-butanol & n-octanol leads to a decrease the NO_X emissions [83].

The highest NO_X of 849 ppm was observed for JOME100 at full load condition and the lowest NO_X emissions of 662 ppm were registered by mineral diesel fuel. As discussed the addition of n-butanol and n-octanol in biodiesel help to decrease the NO_X emissions. Therefore the NO_X emissions of JOME90O10, JOME80O20, JOME90B10, and JOME80B20 were 750 ppm, 768 ppm, 705 ppm, and 730 ppm respectively. It can be seen from the data that the blending of n-butanol reduced the NO_X formation at a faster rate as compared with n-octanol. The reason for this is simple i.e. lower cetane number and poorer heating value of n-butanol compare with n-octanol. The lower cetane number shorten fuel burning interval, lower CV lessens heat release rate during the combustion and higher value of LHV generate a cooling effect in incineration. All those parameters are enough to reduce NO_X emissions to a bigger extent. Similar kinds of trends are observed by various researchers during their study [83], [88], [278]. It was observed that the use of n-octanol by 10% and 20% with JOME reduces the NO_x

emissions by 11.66% and 9.54% respectively at full load condition compared with neat JOME. On the other hand, the use of n-butanol by 10% and 20% with JOME reduces the NO_X emissions by 16.96% and 14.02% respectively at full load conditions compared with neat JOME. The variation of NOx emissions of all blends in percentage with comparison to D100 and JOME100 is depicted respectively in figure 4.40 and 4.41.

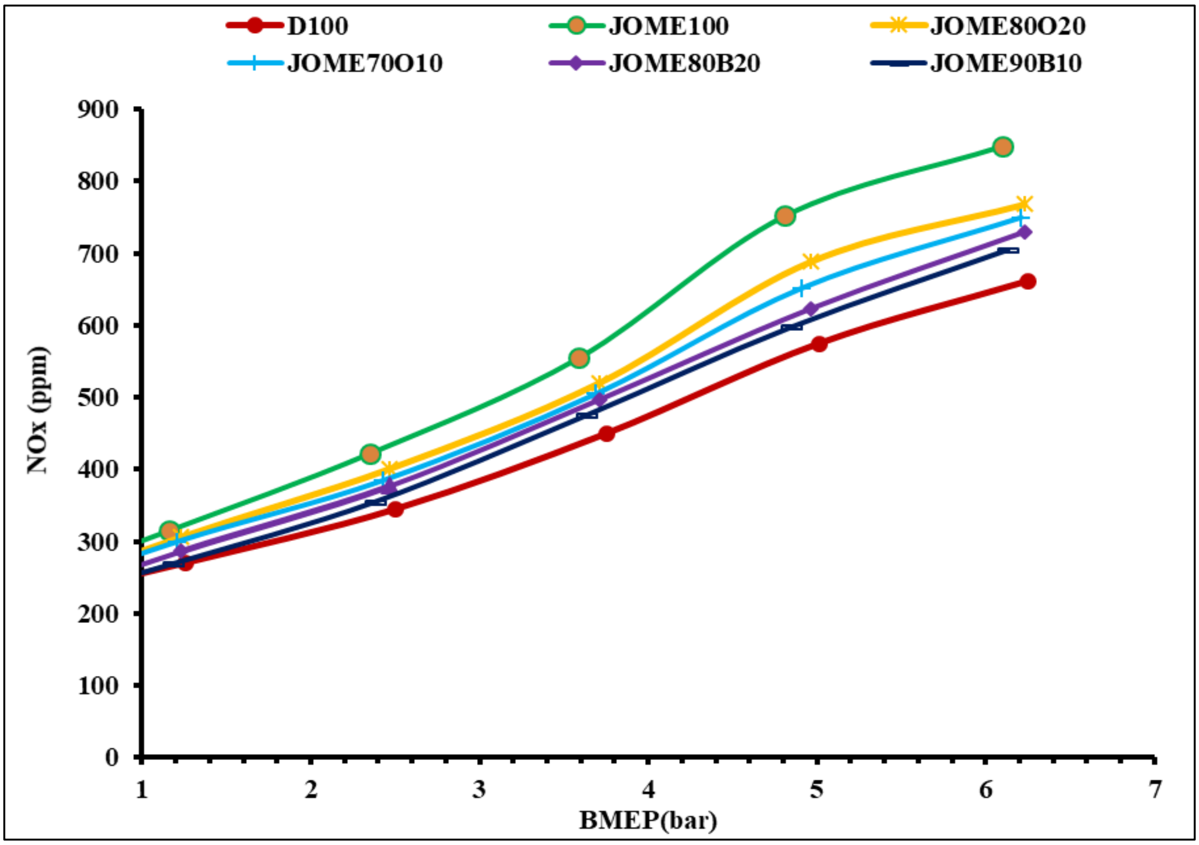


Figure 4.39: NO_X emissions vs. BMEP

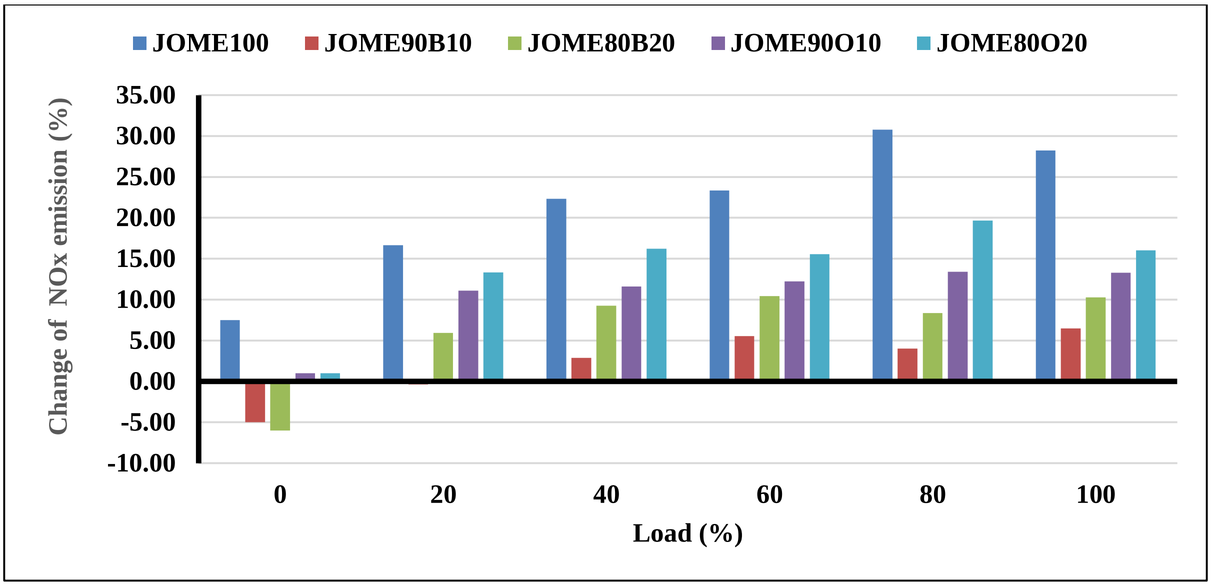


Figure 4.40: Variation of NOx emission compare to D100

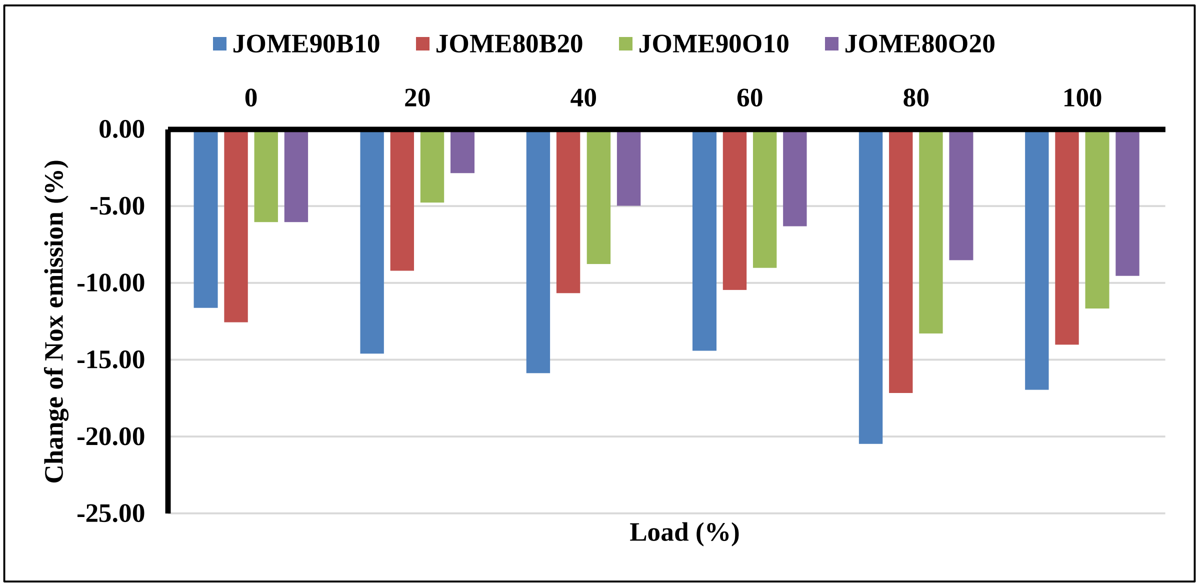


Figure 4.41: Variation of NOx emission compare to JOME100

4.7.3. HC emissions

The emissions of hydrocarbons in any internal combustion engine represent the amount of fuel remain unburnt during the combustion stroke. The hydrocarbons emissions were found higher in the CI engine as a similitude to spark ignition engines. The SI engine generally has homogeneous combustion as thoroughly mixed A/F charge is introduced in engine cylinder through intake stroke. On the other hand, the air is introduced to CC through intake stroke in the CI engine. Further, the charge is compressed during compression stroke then fuel is injected which forms a heterogeneous mixture. Therefore chances of formation of richer and leaner F/A mixture zone inside CC are higher in CI engines.

The incineration process of the CI engine is also complicated as compared to the spark ignition engine, therefore the number of various processes takes place in a shorter period of time simultaneously like atomisation of fuel, ignition delay, self-ignition of fuel, and travel of combust flame. All these processes lead to improper combustion of fuel and results in higher hydrocarbons emissions. Apart from all these reasons, some other properties also affect hydrocarbon emissions like engine speed, engine operating condition, the cetane number of fuel, fuel composition, amount of oxygen present in the fuel and fuel blends, etc. [254].

The dissimilarity of hydrocarbon (HC) outages of a stationary diesel engine using various test fuels with respect to various loading conditions is presented in figure 4.42. HC emissions of conventional diesel engines were observed highest amongst tested fuels for all loading. The HC emissions increased along intensify load for all test fuels but the HC emissions for diesel engines increased at a faster rate with the load as compared to other test fuels[278]. In other test fuels, JOME80B20 showed the highest HC emissions for all loading conditions. At complete throttle, opening HC emissions of mineral diesel were 76 ppm followed by JOME80B20, JOME90B10, JOME90O10, JOME80O20, and JOME100 which has HC emissions of 72ppm, 70ppm, 67ppm, 63ppm, and 60ppm respectively.

It was observed from the result that the blending of alcohol in JOME enhances the HC emissions of the engine for full loading situations. The main reason for increased HC outages for alcohol is a lower cetane number of alcohols as compare to JOME. In alcohols as well n-butanol was responsible for higher HC emissions as compare to n-octanol. The reason for this is the cetane index of n-butanol is much less than the cetane index of n-octanol which affects the combustion and higher value of LHV produce quenching effect in combustion, leads to higher HC emission.

The utilisation of JOME decreases HC exhaust outage of engine for as much higher cetane index& availability of free oxygen. Greater cetane index decrease ignition delay&provides more time for combustion and leads to lower HC emission. A similar trend of HC emissions for different biodiesel is reported by various researchers in their research [9], [89].

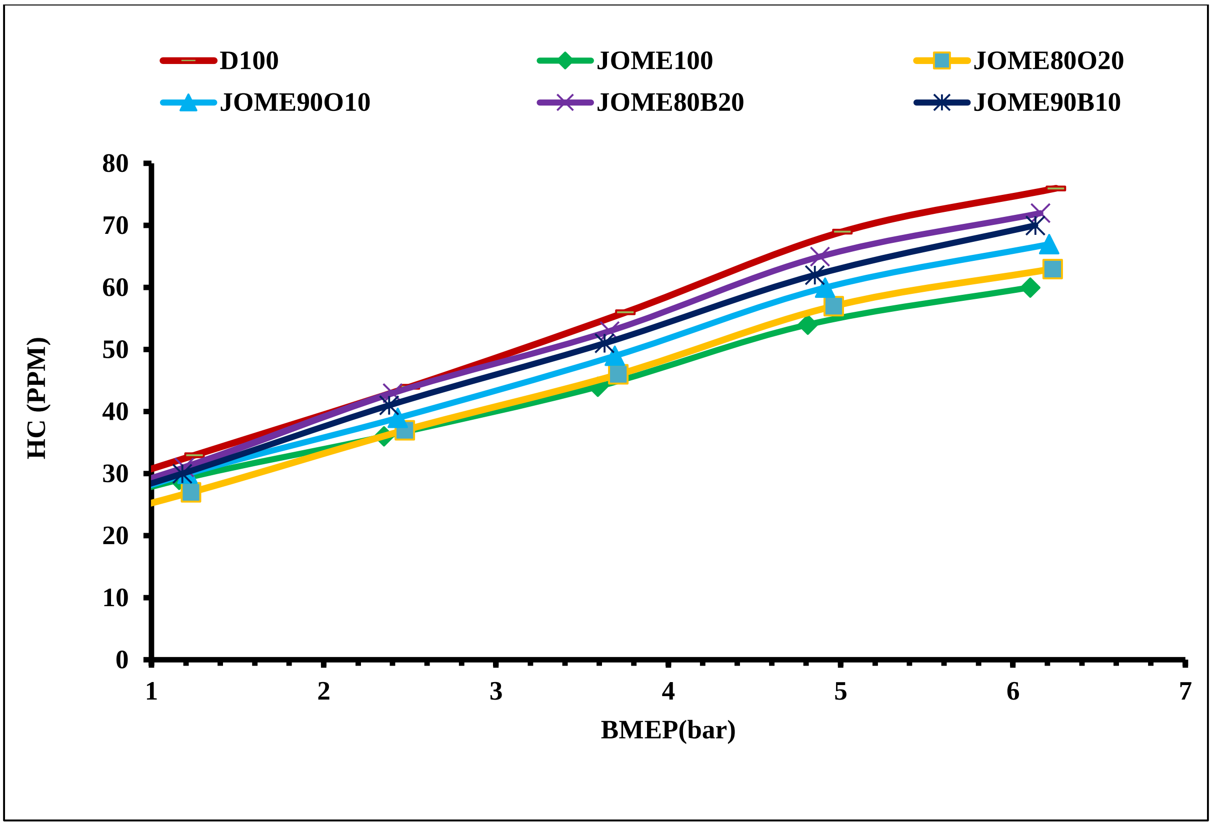


Figure 4.42: HC emissions vs. BMEP

Imdadul et al.[281] used three fuel mixture to scrutinise emissions characteristics of the engine at various engine speeds. The author found, utilisation of ternary mixture increase HC emissions of the engine at a lower speed but as speed increases the HC emissions of the engine decreases. The author analyse that the decrease in HC emissions with increasing speed was due to lower swirling speed of air at low speed which causes lengthier Ignition delay results in higher HC emissions. But the swirling speed increases with engine speed & decreases ignition delay period and HC emissions reduce. Different ternary fuel combination was used by Sidharth and Kumar [84] and evaluated the performance & emissions of the stationary engine. The author also found that the mixing of biodiesel & n-octanol along petrodiesel led to lower HC emissions as compared to normal diesel fuel. The variation of HC emissions as compared to D100 and JOME100 in percentage and depicted in figure 4.43 and 4.44.

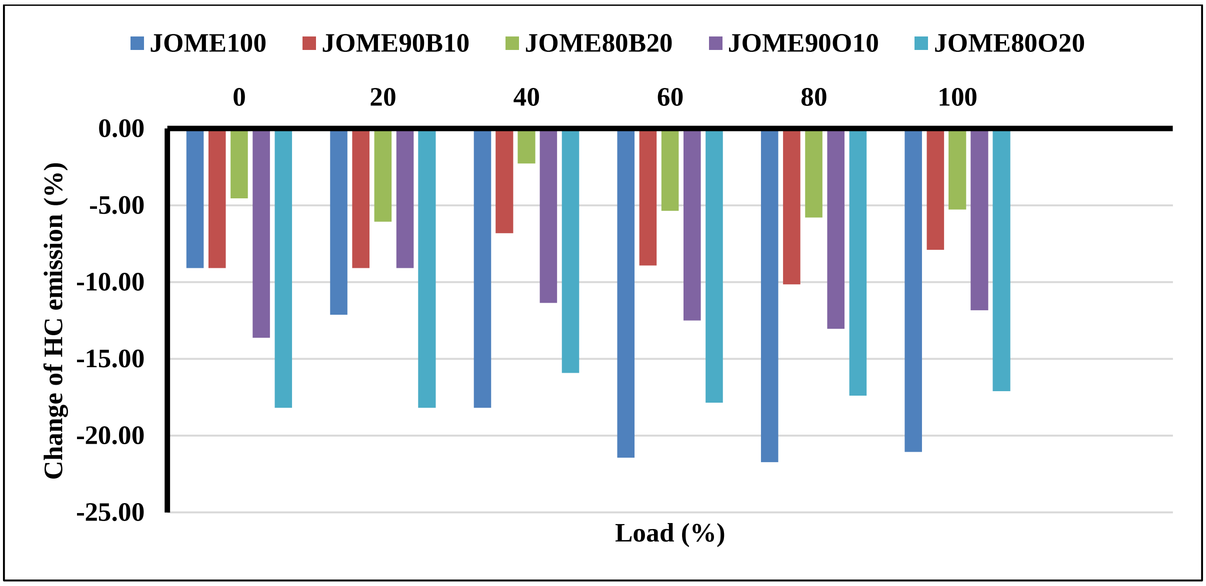


Figure 4.43: Variation of HC emission compare to D100

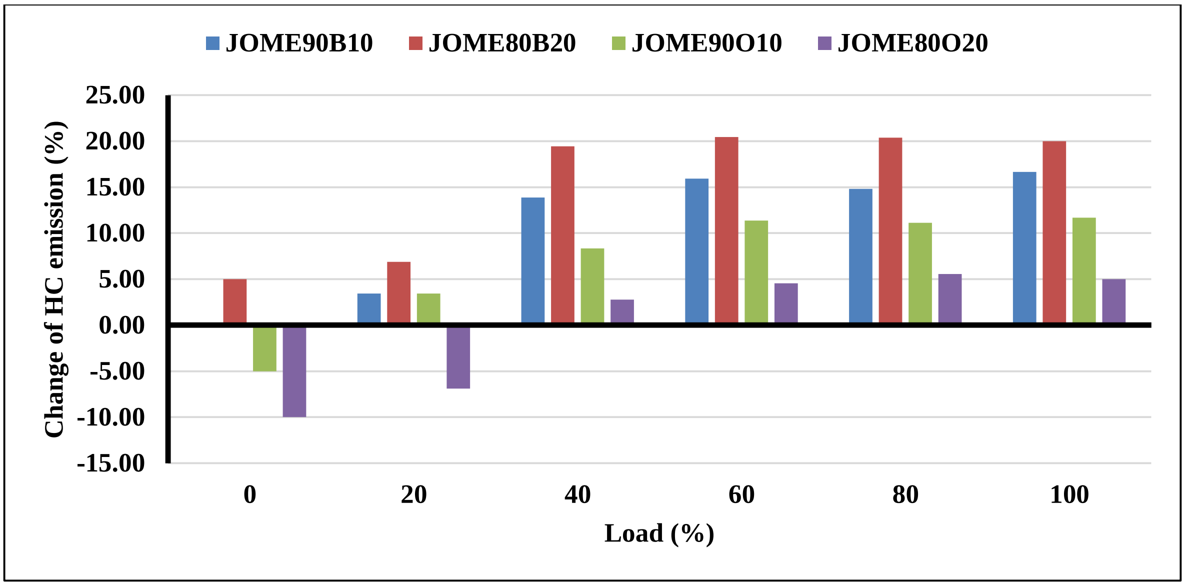


Figure 4.44: Variation of HC emission compare to JOME100

4.7.4. Smoke opacity

The poor atomisation of fuel in the compression ignition engine causes various problems for emissions characteristics of the diesel engine. The poor atomisation leads to upsurge ID& poor vaporisation of fuel increases soot formation of the engine. The soot and incomplete combustion of fuels are the main reasons for higher smoke emissions. Smoke opacity of diesel engines using various test fuels was analysed and correlated with conventional petrodiesel in the present section. The changes in smoke opacity of engine using different test fuels w.r.t. BMEP revealed in figure 4.45.

The smoke opacity of the engine increases with load for all test fuels. The reason for that fuel supply upsurges to the cylinder with an increasing load to fulfill the energy requirement at that load. The smoke opacity of normal diesel operation was utmost as compared to all other fuels. A higher cetane index of the biodiesel that decreases the delay period of the fuel and self-contain of oxygen enhances the combustion. The variation in smoke opacity of test charges was insignificant at no load and low load condition however it increased respectively to load and at advanced at full load condition variation is adequately high & perceived in figure 4.45.

Smoke opacity of engine decreases while alcohol blended JOME was used as fuel. That implies, the use of alcohol decreases smoke opacity of the engine. The blend of higher alcohol reduces the KV, density, and flash point of biodiesel, causing improvement in atomization and proper mixing of air fuel & results in inferior PM emissions [282]. Utilisation of n-butanol in blends impacts more on smoke opacity reduction as compare to n-octanol. After going through the literature it is observed that the reason for that is lower viscosity of fuel which helps the fuel to atomise faster and improve combustion characteristics [283]. The lower free oxygen content and higher carbon molecules in n-octanol as compare with n-butanol caused the marginally higher smoke opacity of n-octanol blends. Intensification inattentiveness of higher alcohol in mixture decrease smoke opacity of engine in the present study. Similar results were also noticed by Zhang et al. [284] and Ashok et al. [204].

The smoke opacity of mineral diesel was 89% at full load which was utmost among all test fuels and all loading conditions. The smoke opacity of JOME100 was second highest after mineral diesel fuel. The smoke opacity of JOME100 was 83%, however, the smoke opacity of JOME90O10, JOME80O20, JOME90B10, and JOME80B20 were 78%, 74%, 68%, and 65% respectively. This is already discussed earlier that the increase in the percentage of alcohol in blend decreases the smoke opacity of the engine. The comparisons of smoke opacity variation compared with D100 and JOME100 is shown in figure 4.46 and 4.47.

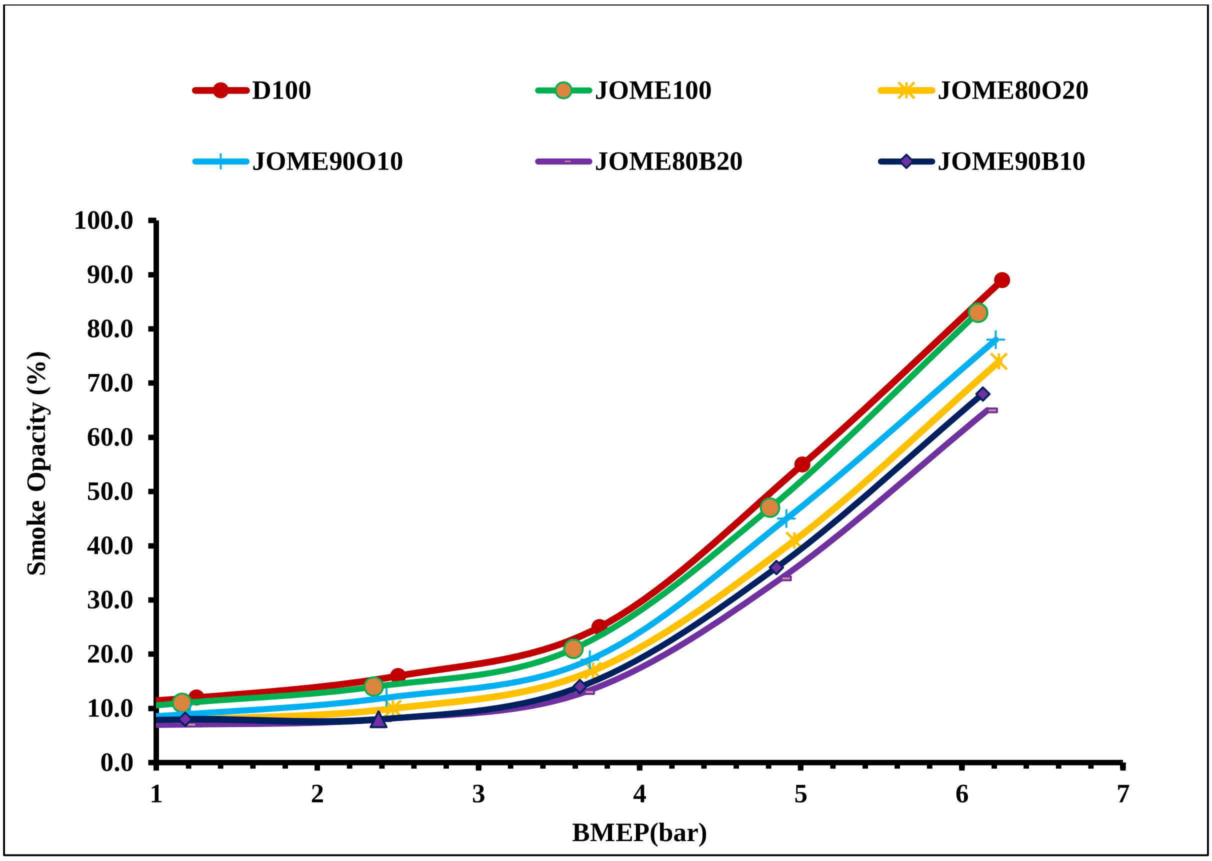


Figure 4.45: Smoke opacity vs. BMEP

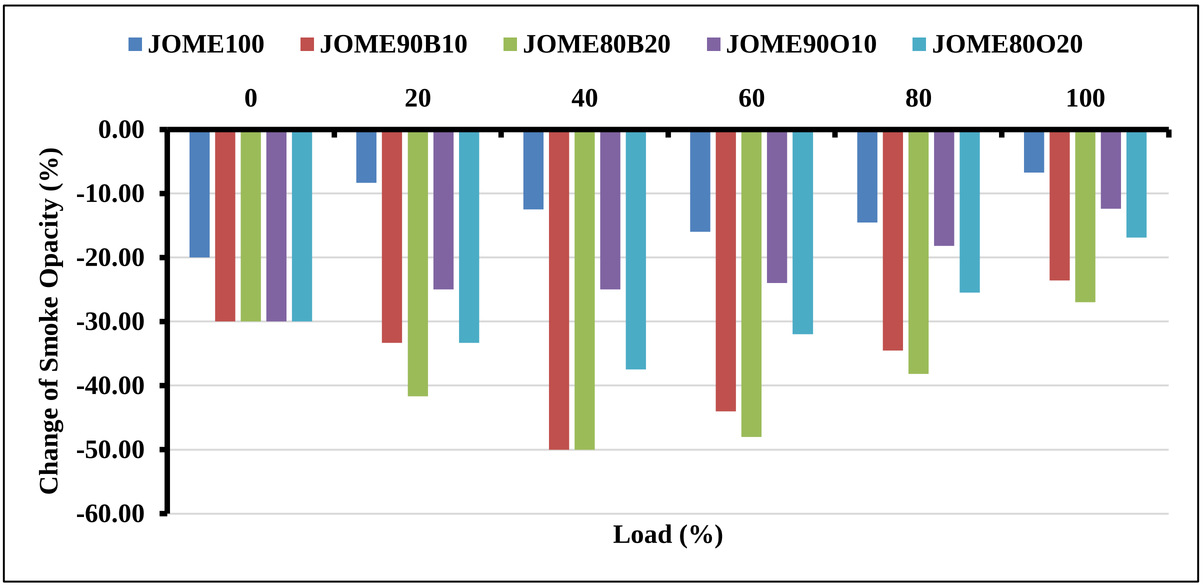


Figure 4.46: Variation of smoke opacity compared to D100

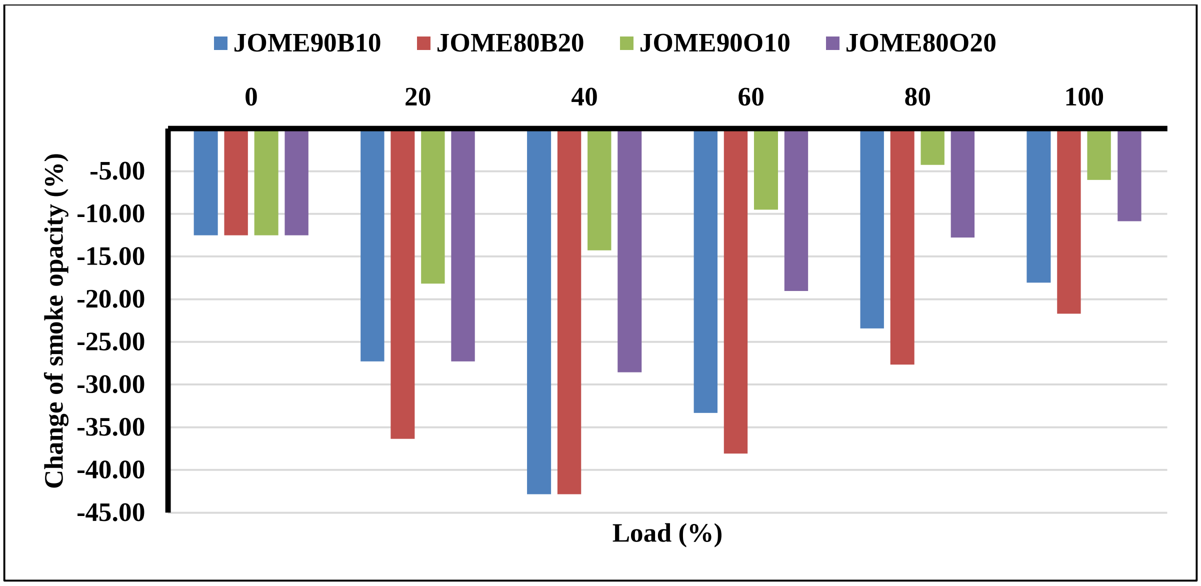


Figure 4.47: Variation of smoke opacity compared to JOME100

4.7.5 Exhaust Gas Temperature

The EGT depends upon the various fuel properties along with the combustion behavior of fuel inside of the cylinder. The calorific value, cetane index LHV, fuel air ratio played a foremost character in EGT. It was pertinent to mention that EGT was going to increase corresponding to increasing load since additional fuel is injected to fulfill the vitality requirement. The EGT of biodiesel was more, in the initial stage due to the higher cetane index of biodiesel hence fuel burning started in pre mixed stage, then further going down owing to higher viscosity causing poor atomization. The JOME has a poor volatility constituent than diesel that burns in the post combustion stage causing higher EGT. The blend of n-octanol was lowering the EGT but still a little higher than a blend of n-butanol. EGT of JOME90O10 was more than JOME80O20 because the latent heat of evaporation is dominant than other factors. The blend of n-butanol with biodiesel was observed lowest among all other mixture due to lesser CV & excessive LH of evaporation compare with n-octanol. Rakopoulos et al. [285] observed that an amassed proportion of biofuel in a mixture of petrodiesel inside the cylinder the EGT was going down due to an increasing proportion of oxygen contained in the fuel. The self-contain oxygen in biofuel increases the air fuel ratio consequently fuel burn leaner. It was observed for the trend of the blend of JOME and n-butanol in present work. The EGT of the blend JOME80B20 was lowest mainly due to maximum oxygen contain, higher LHV, and lowest calorific value of blend. The EGT of blend JOME100, JOME90O10, JOME80O20, D100, JOME90B10, and JOME80O20 were observed 308.64^0C, $298.65\ ^0$ C, 287.69^0C, 281.23^0C, 265.61^0C, and 256.32^0C correspondingly shown in figure 4.48.

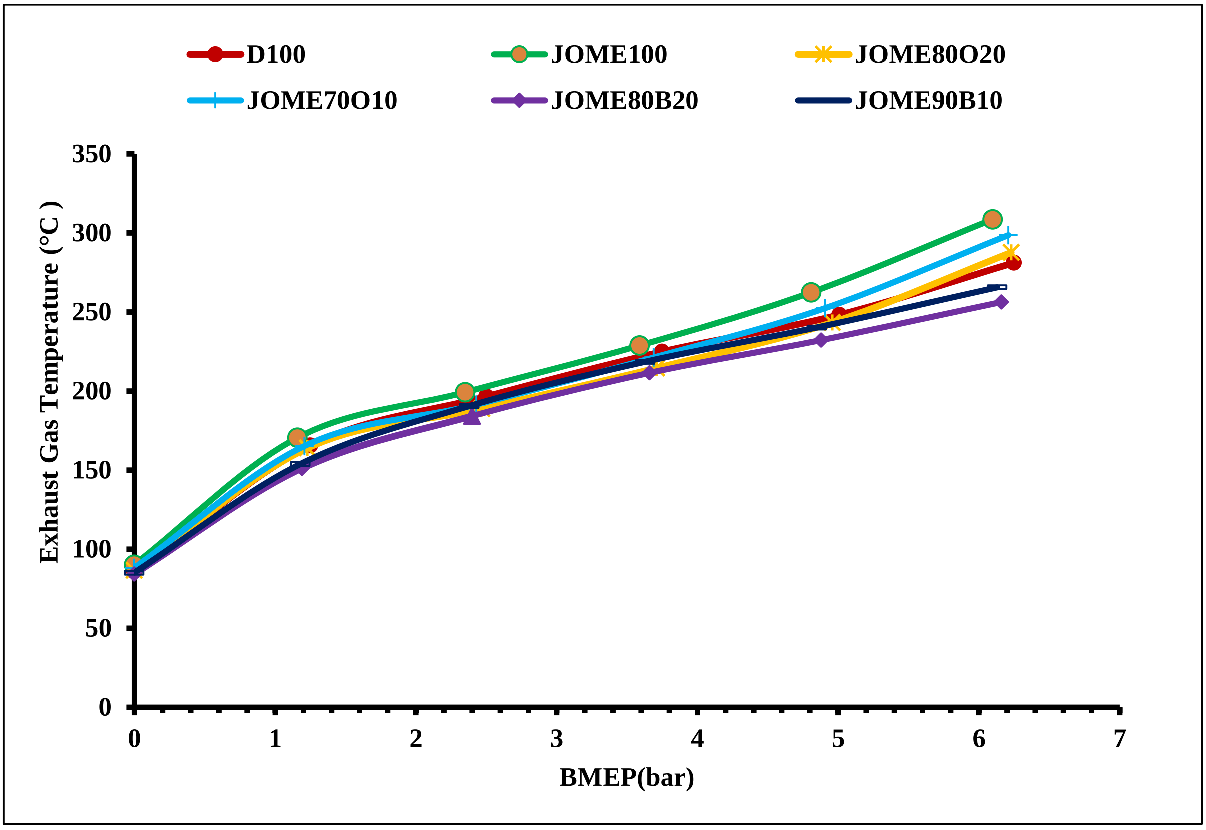


Figure 4.48: EGT vs. BMEP

4.8. Engine’s Combustion Characteristics

The conventional diesel engine is one form of a heat engine in which one form of energy is converted into another form of energy. The fuel used is made up of hydrocarbons which are a very good source of energy. This energy is available in the form of chemical energy which is converted into heat energy in the combustion chamber. The combustion process is a chemical progression of fuel react with oxygen present in the air and converted into final products which are CO_2, H_2O, and nitrogen theoretically. However, the actual combustion is much complicated that what exactly shown during the chemical reaction. The heat energy released during combustion depends upon the combustion characteristics of fuel.

The heat energy generated during combustion increases temperature & pressure which can be analysed with mass fuel burn and the help piezo pressure sensor fixed in the engine cylinder head. The change in inside cylinder pressure against crank angle rotation is measured as per the method explained in chapter 3. Therefore, only inside cylinder pressure is restrained for combustion characteristics of the engine other parameters like heat release rate, rate of pressure rise, cumulative heat release, and mass fraction burnt are analysed with the help of inside cylinder pressure data. The inside pressure mainly depends upon the engine hardware design and combustion characteristics of fuel which is the main function of calorific value, viscosity cetane index, flash point temperature, etc. All the combustion characteristics of fuel and engine are highlighted in detail during this section.

4.8.1. Inside Cylinder Pressure

The inside cylinder pressure of the engine keeps on changing when the engine is in running condition. The inside cylinder pressure change mainly due to two reasons: (i) movement of the piston and (ii) burning of fuel during the power stroke. The change in inside cylinder pressure due to the movement of piston can be calculated with the help of a simple thermodynamic process while the change in inside cylinder pressure due to the combustion of fuel is bit complicated and rise in pressure keep for a very shorter period of time. Therefore to analyse the effect of fuel combustion on inside cylinder pressure one piezoelectric instrument was mounted in the head of the cylinder which was synchronized to PC through data acquisition device. The combustion of fuel can be analysed by sensing the thermodynamic properties. Here the thermodynamic properties were measured to analyse the combustion properties.

The inside chamber pressure of the stationary engine, using altered test fuels, w.r.t. crank angle (CA) rotation at full load is represented in figure 4.49. Furthermore, JOME100 shown higher ultimate pressure as compare to mineral diesel at full load. The uttermost pressure of JOME100 is due to its higher cetane index& density [228]. Uttermost inside cylinder pressure for JOME100 was 71.95 bar which was higher than peak pressure of baseline data of D100which has peak pressure of 71.04 bar. The other fuels JOME90O10, JOME80O20, JOME90B10, and JOME80B20 were 70.05, 72.68, 68.17, and 69.15 bar correspondingly. Blending of n-octanol decreases the peak pressure in the JOME90O10 but further increase in the percentage of n-octanol results in higher peak pressure. This was observed cetane index of n-octanol is an inferior similitude to JOME. So 10% blending of n-octanol does not decrease the cetane index to so low that it intensifies the blazing deferral period but it improves atomisation property of fuel which leads to smooth combustion and results in lower peak pressure. Additionally, intensification in the gratification of n-octanol in amalgams increases the ID result, more time available for proper mixing combustible mixture, and more fuel burn in a short period that cause higher peak pressure. The n-butanol has much lower cetane index and CV among all parent fuels, therefore, its content in the blend with JOME decreases the cetane Index, calorific value, and viscosity of the blend and comes along lower the peak inside cylinder pressure. However, blend JOME90B20 exhibited better burning characteristics than blend JOME90B10 owing to lower viscosity and higher ID. Sahoo and Das [286], Rakopoulos et al.[287], and Nour et al.[259] observed similar trends while comparing the combustion of biodiesel with diesel, blend of butanol, and biodiesel with biodiesel and blend of n-butanol, n-octanol, and diesel with diesel correspondingly.

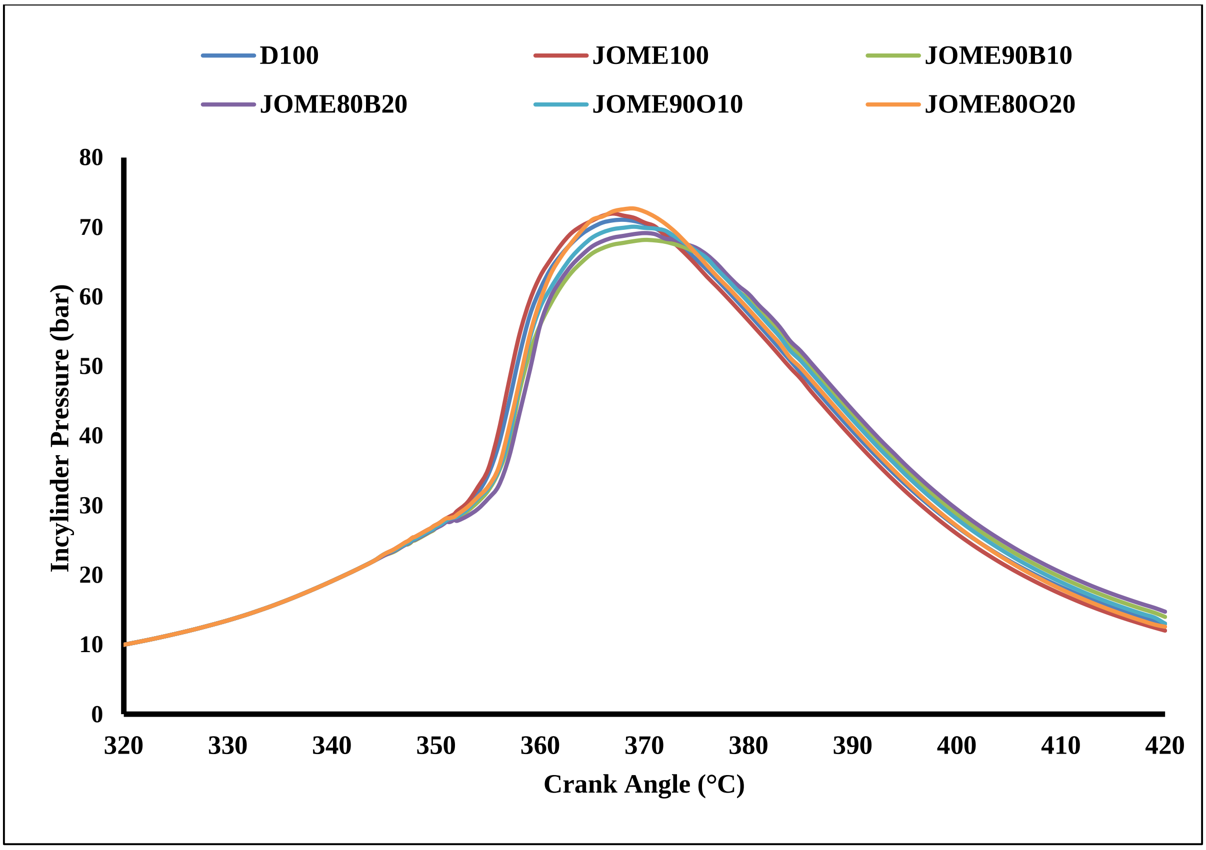


Figure 4.49: Inside cylinder pressure vs. CA

4.8.2. Heat release rate

The HRR per degree crank angle (CA) shows incineration physiognomies of fuel inside the combustion chamber at the particular condition. It is found that the furthermost of the heat is releasedaround10^{0} of crank displacement after the starting of combustion. The HRR of various test fuels in constant speed stationary engine is analysed for all loading conditions however the result for full load is presented in this section. Additionally, HRR upsurges with an increase in load and found extreme at full load condition, since more fuel is added to achieve the energy necessity which is presented in this section [288].

. As already discussed the speed of the engine retained fixed at 1500 rpm for all loading conditions so it becomes easy to analyse the HRR for various fuels at maximised load. The

HRR is premeditated from records gotten from measuring inside cylinder pressure. The methods and equations used for the computation of HRR are already explained in chapter 3.

It is found from the study that higher the peak pressure results in developed HRR for that fuel. Higher uttermost pressure achieved due to the sudden combustion of large amounts of fuel in a shorter period of time. Therefore the sudden combustion of more quantity of fuel in shorter crank angle rotation leads to a higher heat release rate at that period of time. The heat release rate of all tested fuel at maximum capacity is represented in figure 4.50. The HRR is calculated for per crank angle rotation.

At the commencement of the graph a negative heat release (HR) was perceived due to evaporation of added fuel in delay period and heat transfer (HT) to cool engine cylinder wall when combustion is started, it’s become positive. The maximum HR of all blend marginally lower than diesel because of higher viscosity and lower CN of a blend, increase the delay period which is dominated in the later stage of incineration [277]. Ignition of biodiesel starts earlier due to higher cetane index comparison to other blends so it burns its premixed stage and HRR was more in earlier stage compared to other blend but poor atomization of biodiesel due to higher viscosity HRR was lower in controlled combustion phase. Highest HRR was noticed for mineral diesel fuel of 62.22 J/°CA among all test fuels owing to higher CV. The peak heat release rate of JOME100, JOME90O10, JOME80O20, JOME90B10 and JOME80B20 was 56.88 J/°CA, 60.05 J/°CA, 60.95 J/°CA, 57.24 J/°CA& 58.84 J/°CA respectively. It is perceived, blending of n-octanol and n-butanol increases HRR of blends however, the presence of n-octanol impacts more on the heat release rate. The addition of n-octanol proportion in blends improves the combustion properties of fuel and a large quantity of fuel burn in a shorter period of time. The same effect is given by n-butanol but the calorific value and density of n-butanol are very less as compare to n-octanol, therefore, the heat release rate of JOME and n-butanol blends are less as compare to JOME and n-octanol blends. The JOME100 shows the lowest heat release rate among all test fuel, the higher kinematic viscosity is the main reason for that. Higher kinematic viscosity & density decrease atomisation rate and slower combustion and decrease in heat release rate. These outcomes are analogous to Nanthagopal et al. [278].

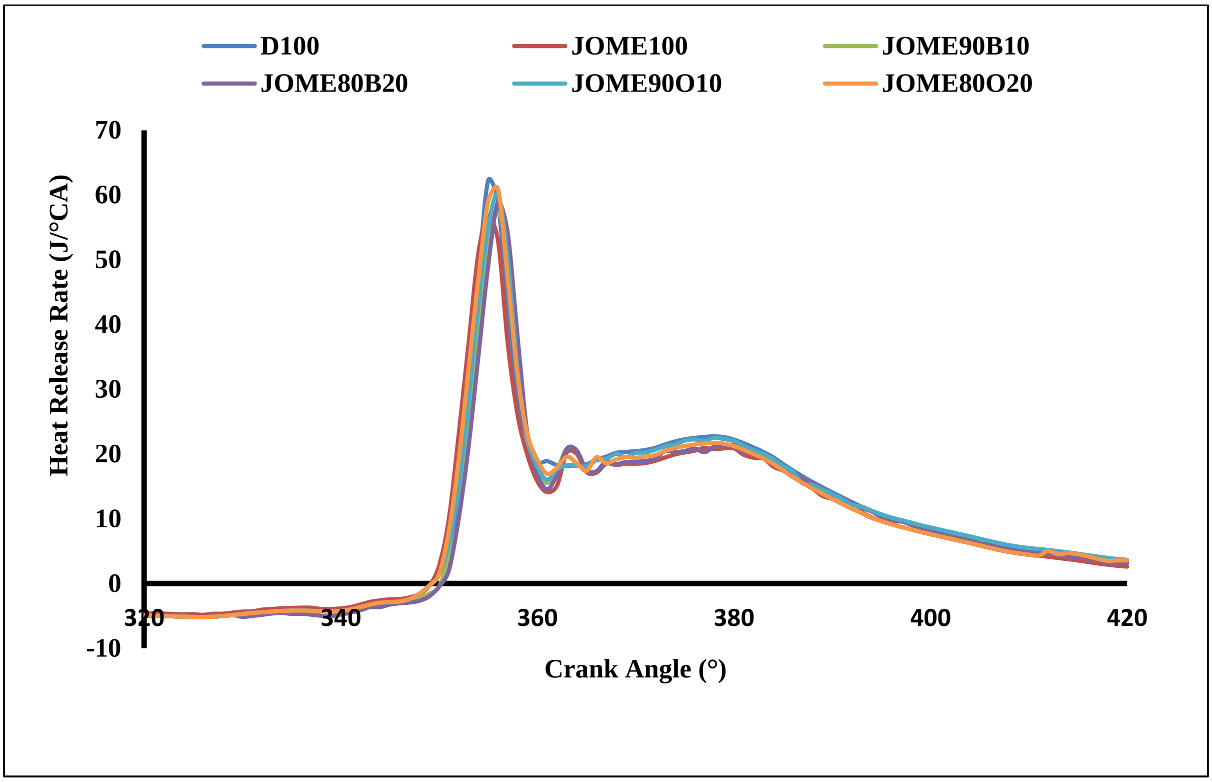


Figure 4.50: HRR vs. CA

4.8.3. Pressure rise rate

The pressure rise rate (PRR) inside the engine cylinder represents the rate of force applied by the combust gases on the piston of the engine. As the load on the engine intensifies, more force is required to thrust the piston from TDC to BDC. Therefore more fuel needs to combust to fulfill the requirement of force. As discussed during the inside cylinder pressure section that the pressure varies with the thermodynamic relationship inside the cylinder until combustion starts. Therefore the pressure growth rate depends upon the demeanor of piston and rate of heat release. In simple words, the pressure growth rate is a differential representation of HRR. Hence the trend of pressure growth rate is nearly similar to the HRR curve. The rate of pressure rise Vs. CA is presented in figure 4.51.

The PRR also use to analyse the fatigue load applied on engine piston and this helps in fixing the piston service period. If the service does not take place on time it may cause the failure of the piston and its parts. The highest PRR was noticed by petrodiesel. This may be attributed to rapid burning in uncontrolled combustion. The reason for the rapid burning of petrodiesel may be attributed to higher calorific and lower viscosity. The lowermost PRR was saw for JOME100 among all tested fuels. The reason behind that for lower PRR of JOME100 is higher KV, which may cause less fuel burn in the premixed burning phase[289]. Apart from that lower CV and poor volatility are also other factors for lowering the PRR of JOME100 [290].

The crowning pressure growth rate of petrodiesel was found 6.67 bar/°CA at maximum throttle. The peak PRR of JOME100, JOME90O10, JOME80O20, JOME90B10, and JOME80B20 were 5.45, 6.17, 6.38, 5.63, and 5.94 bar/°CA. This trend is similar to HRR, as PRR depends upon HRR only. The RPRs of 20% blend of n-octanol and n-butanol has shown more PRR due to higher ID and lower flash points, than the corresponding blend of 10% blend. The blend of n-octanol demonstrates more PRR owing to a higher calorific value than a blend of n-butanol.

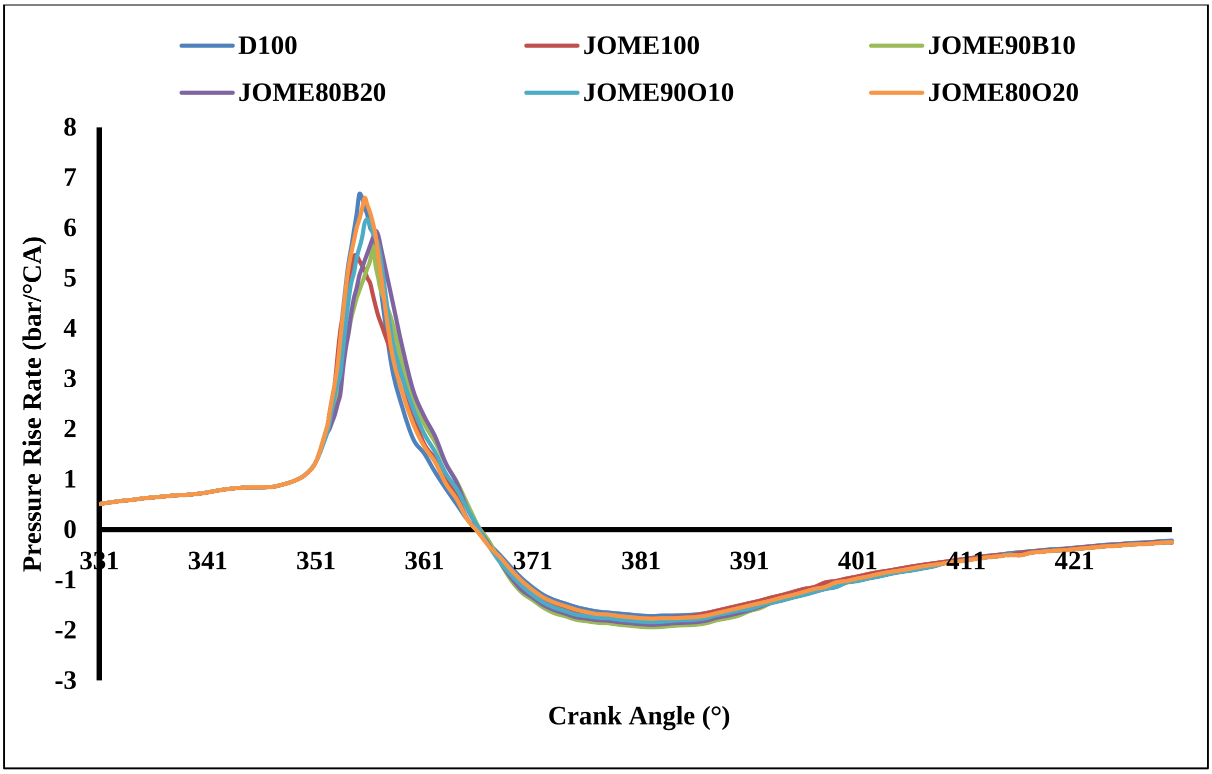


Figure 4.51: Pressure rise rate vs. CA

4.8.4. Cumulative heat release

The CHR is the sum of the heat discharge during the combustion of fuel in that stroke up to that crank slant position. The CHR is calculated by totalling of HRR value respectively rotation or by integrating HRR respective to CA and with an increasing factor of heat release coefficient. The detailed procedure of calculating cumulative heat release is explained in chapter 3. The HRR expresses qualitative evidence of the burning of fuel whereas CHR shows the quantitative evidence regarding the progress of incineration of fuel. The variation of CHR respective to the CA revolution for all tested fuels is publicized in figure 4.52. As discussed earlier the CHR depends upon HRR, therefore, all test fuels followed the same sequence as followed during HRR.

The factors affecting the CHR of various test fuels are cetane number, calorific value, density, kinematic viscosity, atomisation of fuel, etc. The cumulative heat release begins with the initiation of incineration & finish with the termination of the incineration. As discussed it is the progressive summation of HRR respective to CA rotation. Similar to the heat release rate the mineral diesel shown the highest cumulative HRR at maximum throttle. The main reason for this is higher calorific value & better atomisation property of mineral diesel fuel as compared to other test fuels. The JOME100 shown the lowest cumulative heat release due to poor volatility, higher flash point, KV, lower flame speed. The adding of n-octanol and n-butanol increases the cumulative heat release of blends but remains less than mineral diesel fuel. The higher calorific value and cetane number of n-octanol help to increase the cumulative heat release to a higher extent compared to n-butanol. The identical result is obtained by Ramesh et al. [291] and Nour et al. [259].

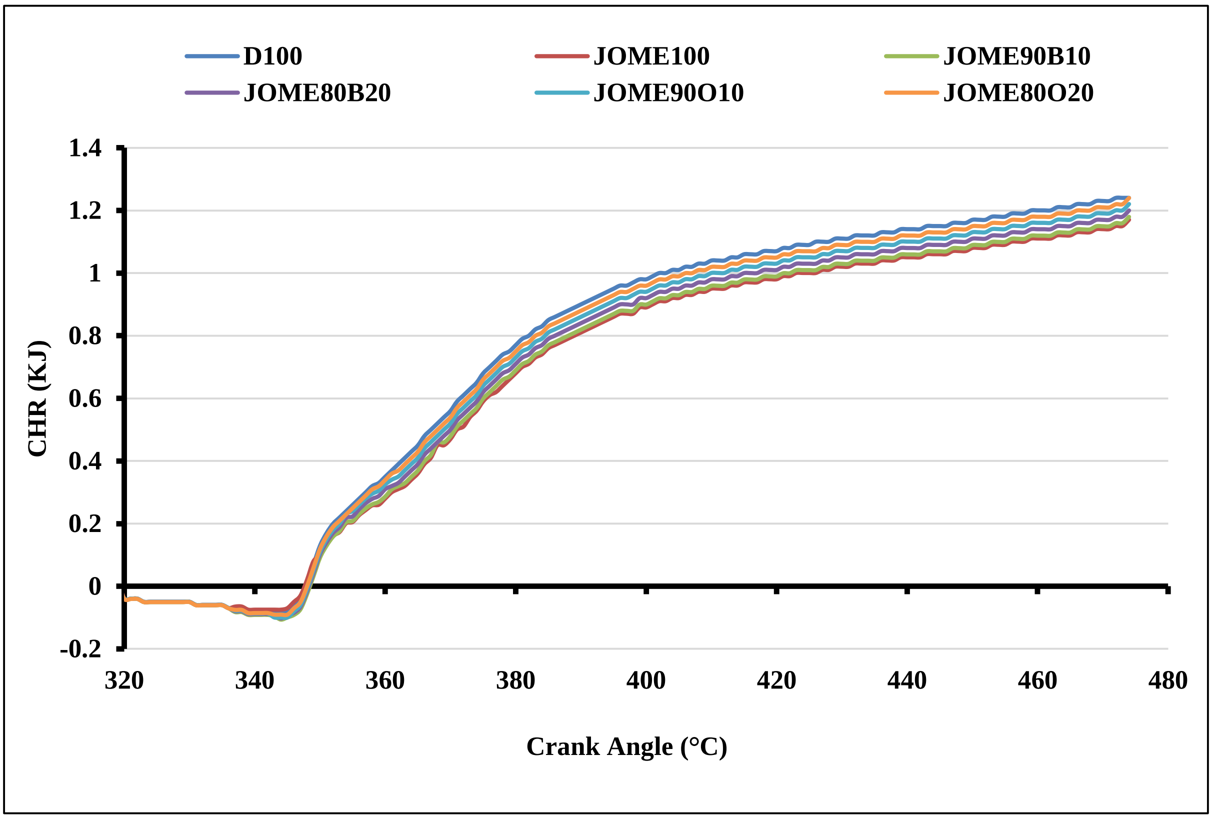


Figure 4.52: CHR vs. CA

4.8.5. Mass fraction burnt

The MFB represents the efficiency of the fuel combustion process inside the combustion chamber at the various operating condition. In the present section, the full load condition is selected to analyse the fuel combustion efficiency of the engine. As already discussed that combustion is the process of transformation of chemical energy present inside fuel into heat energy by reacting with oxygen at the suitable thermodynamic condition. Therefore, the mass fraction burn can also be defined as the part of injected fuel burnt during the combustion process with crank rotation. The mass fraction burnt performs an imperative part in the IC engine as the power generates by the engine is proportionate to the amount mass of fuel burnt during that process. The mass fraction burnt is scaled between 0 to 1 or 0% to 100% if considered in the percentage. Jamrozik et al. [253] divided the mass fraction burnt into two major parts i.e. blazing deferral part and extent of fuel burning. According to the author, the ignition delay period is demarcated, time from initiation of inoculation of fuel, and instant at which 10% of the fuel is combusted in the combustion process. The second stage of combustion is the extent of starting 10% to 90% fuel combustion. The mass fraction burnt of all test fuel respective to CA rotation at maximum load is revealed in figure 4.51. The combustion of JOME100 starts earlier as compare to other tested fuels and petrodiesel. Therefore, MFBfor JOME100 was higher in the initial movement of the crank rotation. The earlier burning of JOME100 is because of a higher cetane index which decreases the ID. The blending of n-octanol decreases the CI of the blend but it still parallel to petrodiesel. So, the combustion of JOME & n-octanol blends starts earlier as compare to mineral diesel owing to the molecular oxygen content in fuel. Further, it can be said that the mass fraction burnt during the ignition delay period was more for JOME100 and blends of JOME and n-octanol as compare to mineral diesel fuel. A similar trend was observed by Ramesh et al.[291] and Wang et al. [292] when used a blend of diesel -biodiesel and diesel, biodiesel with butanol and hexanol.

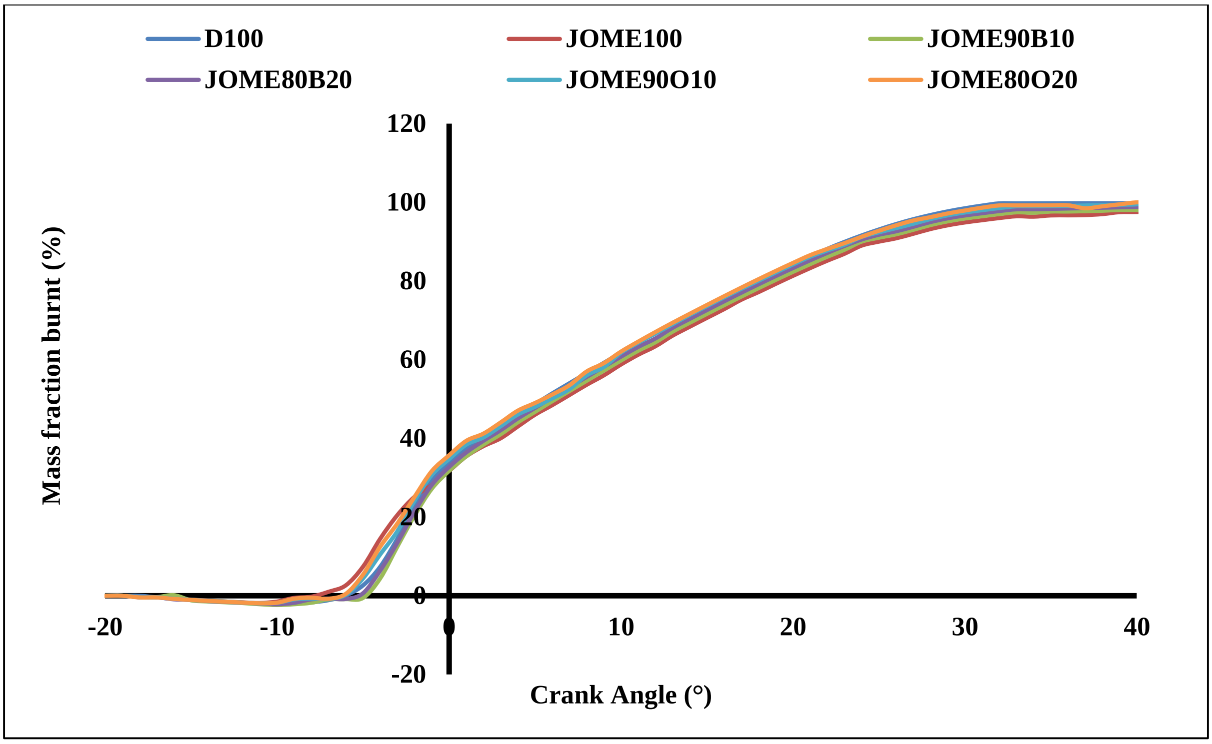


Figure 4.53: MFB vs. CA

The addition of n-butanol decreases the cetane index of the mixture to a large extent which leads to late in combustion. The temperature & pressure inside the combustion chamber increases which nullify the chemical delay period. Now cetane number not more responsible for ignition delay the factor that affects the ignition delay is atomization property of fuel. Therefore, the combustion rate of mineral diesel fuel increased with a faster rate as compared to other test fuels as mineral diesel has better atomisation properties among all test fuels. Hence, in the second stage of combustion, mineral diesel fuel has the highest MFB at the end of the incineration procedure. On the other hand, JOME100 has poorest atomisation characteristics, therefore, the mass fraction burnt of JOME100 was lowest among all test fuels at the end of the combustion process as portrayed in figure 4.53.

4.8.6. Ignition Delay

The duration amongst instant fuel inoculation & instant of the first spark generated is acknowledged as the ignition delay period. This duration for a particular fuel depends upon its cetane number. In a simple relationship between these two, the ignition delay period (IDP) contrariwise proportions CN. Greater the CN of fuel leads to shorter IDP. The shorter IDP of fuel provides a longer time to combustion and turned to smoother combustion. The IDP of fuel also depends upon fuel properties such as kinematic viscosity, density, and volatility. The JOME100 has the highest cetane number among all test fuels hence the ignition delay period of JOME100 was shortest in all test fuels. On the other hand, n-octanol and n-butanol have lower cetane number similitude to mineral diesel, hence by blending of alcohol in biodiesel reduces the CN of biodiesel but improves the other property of biodiesel as well as combustion performance and emission also owed to lower flash point and volatile in nature [293][253]. Hence, the ignition delay of blended fuels was a higher similitude to JOME100 and mineral diesel. It is observed through the HRR graph thatJOME80B20 shows the highest ID 11.7° CA while JOME100 lowest 9.9°CA and diesel 10.8°CA. Figure 4.54depicted the effect of blending on ignition delay at full load.

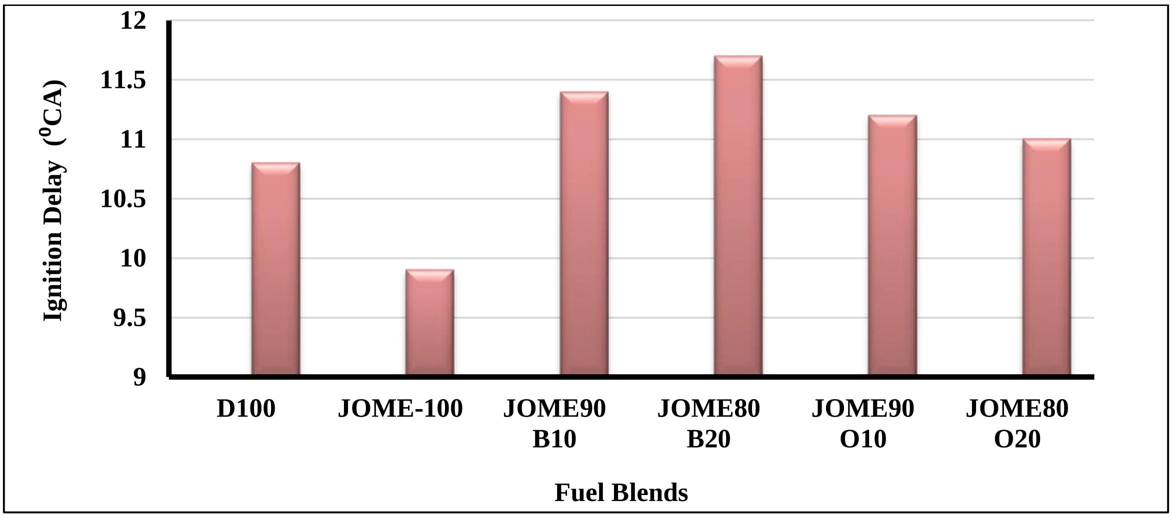


Figure 4.54: Ignition Delay of Fuel and blend

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusions

The major objective of this study is to explore the complete replacement of petroleum diesel with a blend of renewable fuel which can be used in the unmodified small capacity diesel engine, without compromising of performance of the engine and improving the emission quality. The GOI supported feedstock Jatropha was selected for biodiesel production. The biodiesel blends with higher alcohol (n-butanol n-octanol) were prepared and the characterization of the blend was carried out as per ASTM standard. The exhaustive experiment was carried out to evaluate the suitability of the blend of n-butanol/n-octanol with JOME in a small capacity CI engine. However, the blending of n-butanol and n-octanol offered a potential substitute for petroleum diesel. In general, the blend of n-octanol with JOME is shown better results than a blend of n-butanol due to better combustion properties of n-octanol than n-butanol rather than kinematic viscosity.

After browsing the various theoretical and experimental research activities of the present work the following conclusions are coming out regarding the production of biodiesel fuel, optimization of the production process, preparation of blends, characterization of the blend, performance, emission, and combustion analysis.

- The Jatropha is the most versatile inedible oil for low-cost biodiesel production. As well as higher alcohols like n-butanol and n-octanol have similar properties of mineral diesel which can be produced from biomass.
- The reduction in FAA was observed from 7.1% to 1.7 %, during the esterification process by adopting of optimised parameters i.e. the catalytic concentration of 1.13, reaction temperature 58°C reaction time 67 minutes, and molar ratio 6.35.

- While the yield of biodiesel production was maximized up to 96.63 % in transesterification by adopting the RSM in production optimization. During the yield production of biodiesel, the parameters were molar ratio 7.52, the catalytic concentration of 0.83, reaction temperature 48°C reaction time 72 minutes.
- The blend of 10% and 20% by volume of n-butanol and n-octanol with JOME prepared separately. The physicochemical properties of the test blends were compared to diesel and found to be comparable and within the ASTM prescribed limits.
- The blend JOME80O20 gave 18.34% higher BTE than JOME100 but 2.23% lower than diesel at 80 % load.
- The n-octanol blends emit lower CO due to better combustion property to the n-butanol blends.
- HC emission of all blend was lower than diesel due to oxygenated fuel but JOME80B20 emits the highest HC among all blends because n-butanol has a lower boiling point and higher LHV which create quenching effect in combustion while JOME80O20 shown lowest HC emission 63 ppm rather than JOME100.
- It was observed that NOx emission of the blend of n-octanol was lower compare to JOME but marginally higher than the blend of n-butanol owing to the higher latent heat of evaporation of n-butanol than n-octanol.
- JOME80B20 revealed the least smoke opacity 65%, because of n-butanol contain more Oxygen and lower carbon content than n-octanol.
- The n-butanol has a higher latent heat of evaporation and Lower calorific value compare to n-octanol consequently decrease the EGT. The JOME80B20 demonstrated lowest EGT 256.32°C while JOME100 was 308.64°C.

- The blend of JOME80O20 achieved the highest in-cylinder pressure 72.68 bar, owing to its better combustion property of n-octanol. The higher density, lower volatility, and higher ignition delay of n-octanol lead to more fuel burn-in short time causing higher pressure rise.
- The HRR was lowest, 56.88 J/°CA for JOME due to its higher viscosity than other blends while HRR of JOME80O20 highest, 60.95 J/°CA, rather than diesel.
- The JOME80O20 shown higher RPRs 6.38 bar/°CA among all blends of biodiesel except for diesel. While JOME 100 shown the lowest 5.45 bar/°CA due to shorter ignition delay. The RPRs of 20% blend of n-octanol and n-butanol showed higher RPRs owing to higher ignition delay than the respective blend of 10% blend.
- The blend of n-octanol and n-butanol with JOME increased CHRR than JOME in the diffusion state but still lower than mineral diesel due to higher viscosity, surface tension, and lower calorific value.
- Mass fraction of burn rate of JOME 100 in the premixed stage was more due to higher cetane index but lower in diffusion state due to higher viscosity of JOME that impinged the atomization and the air-fuel mixing process. However, the blend of n-octanol and n-butanol increase the mass fraction burnt of JOME in the diffusion state but still it was lower than mineral diesel.
- The blend of the n-butanol showed higher ID comparisons to blend of n-octanol due to the lower cetane index and higher LHV of n-butanol.
- When a higher percentage of n-octanol was used, It was observed that the engine did not run smoothly because the characteristic of the blend was poorly affected by increasing the blend of more than 20 percent.
- The current study concluded that the Blend of n-octanol with JOME showed better performance and overall emission than a blend of n-butanol and JOME. Hence the

blend JOME80O20 is a promising candidate as an alternative to petroleum diesel considering better performance, emission, and combustion characteristics with some consequence on HC emissions.

5.2 Scope for Future Work

Based on knowledge gained during the present experimental work, the following Future scope of work emphasized.

- The very limited work on the synthesis of n-octanol from the biomass platform.
- The current study focused on the use of n-octanol further higher alcohol may be explored as a blend.
- There is a scope to simulate results and compare them to the experimental results for the validation of the computational model. A three-dimensional geometrical model consistent with the actual engine set up may be designed and simulated in ANSYS software.
- Spray flame analysis of blends may be carried out for confirmation of combustion analysis.
- CFD code may be implemented for the Spray combustion simulation.

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