EXPERIMENTAL INVESTIGATION ON PERFORMANCE AND EMISSION CHARACTERISTICS OF NON ROAD CI ENGINES OPERATED WITH CARDANOL BIODIESEL BLENDS

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

MALLIKAPPA

DEPARTMENT MINING ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY

KARNATAKA SURATHKAL, MANGALORE-575025

JANUARY 2014

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DECLARATION

I hereby declare that the Research Thesis entitled **“EXPERIMENTAL INVESTIGATION ON PERFORMANCE AND EMISSION CHARACTERISTICS OF NON ROAD CI ENGINES OPERATED WITH CARDANOL BIODIESEL BLENDS”** which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy in Mining Engineering (Renewable Energy) is a bonafide report of the research work carried out by me. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

Signature of the Research scholar

Place: NITK-Surathkal

MALLIKAPPA

Date: / 12 /2014

Reg.No.MN06P02

Department of Mining Engineering

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CERTIFICATE

This is to certify that the Research Thesis entitled **EXPERIMENTAL INVESTIGATION ON PERFORMANCE AND EMISSION CHARACTERISTICS OF NON ROAD CI ENGINES OPERATED WITH CARDANOL BIODIESEL BLENDS,** submitted by Mallikappa, (Reg.No.: MN06P02) as the record of the research work carried out by him, is accepted as the Research Thesis submission in partial fulfillment of the requirements for the award of degree of Doctor of Philosophy.

Research Guide(s) Signature with Date

Dr.Ch.S.N.Murthy	**Dr.N.Rana Pratap Reddy**
(Research Guide)	(Research Guide)

Chairman - DRPC (Signature with Date and Seal)

Respectfully dedicated to

My Parents and Teachers

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MALLIKAPPA

ABSTRACT

Diesel engines dominate the field of commercial transportation and agricultural machinery because of their superior fuel efficiency. There is a limited reserve of the fossil fuels and the world has already faced the energy crisis of the seventies concerning uncertainties in their supply. Import of petroleum products is a major drain on our foreign exchange sources and with growing demand. Research has shown that, these vehicular emissions are the source of air pollution and have adverse implications on health and air quality. Lead, carbon monoxide, nitrogen oxides, particulate matter and hydrocarbons together with the unavoidable production of carbon dioxide are the harmful components of exhaust gases from internal combustion engines [4].

Energy is considered as a critical factor for economic growth, social development and human welfare. More than 6.5 million diesel engines are being used in the Indian Agricultural sectors for various activities. With increasing trend of modernization and industrialization, the world energy demand is also growing at a faster rate. India, facing the challenge of meeting a rapidly increasing demand for energy, and ranks sixth in the world in terms of energy demand. Its economy is projected to grow 7%-8% over the next two decades and there will be a substantial increase in demand for oil to manage transportation and also to meet various other energy needs.

The primary problem associated with straight vegetable oils as a fuel in diesel engines is caused by high viscosity and low volatility, which, in turn cause improper atomization of fuel during injection and lead to incomplete combustion and result in formation of deposits on the injectors and cylinder heads, leading to poor performance, higher emissions and reduced engine life. The high viscosity of vegetable oils can be reduced by using transesterification process. The concept of transesterification process of non-edible oil with an alcohol provides a clean burning fuel (commonly known as biodiesel) having less viscosity. Its main advantage is that many of its properties are quite close to those of diesel and it can be grown and processed in rural areas. Keeping in view the plight of the energy crisis, in this work cardanol biodiesel has been used for investigation in various single and multi-cylinder diesel engines.

A single cylinder diesel engine was used to evaluate the performance and emission characteristics of cardanol biodiesel. A single cylinder VCR (variable compression ratio) engine was fuelled with volumetric blends of cardanol biofuel and the performance and emission characteristics were compared with petro diesel and PE characteristics were evaluated for 18:1 and 17:1compression ratios. An extended experimental study was conducted on a Kirloskar double cylinder CI engine to evaluate the performance and emission characteristics. The cardanol biodiesel volumetric blends like 0 %, 5% ,10% ,15% ,20% , 25% and base fuel (Petro diesel) were tested at various loads like 0 %, 25 %, 50%,75% and full load, and at a constant speed of 1500 rpm.

From the results, it is found that the brake specific energy consumption decreased by 30 to 40% approximately with increase in load conditions. Brake thermal efficiency increased with increase in load. The brake specific energy consumption decreased by 30 to 40% approximately at higher CR and 25 to 30% at lower CR with increase in brake power. The HC emissions are nominal up to B20, and more at B25, the reason for this being the incomplete combustion. The Nox emissions (ppm) increased with increased proportion of blends and with higher EGT. The Carbon monoxide emissions increased with higher blends, and increased slightly more after 20% blends. From this investigation it is observed that up to 20% blends of cardanol biodiesel may be used in CI engines without any hardware modifications.

Keywords: Fossil fuels, Hydrocarbons, Internal combustion engines, Characteristics, Performance, Emissions, Cardanol biodiesel.

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ABBREVIATIONS

ADC: Analog-to-Digital Converter
ASTM: American Society for Testing and Materials
AOM: After Operations Maintenance
BSI: British Standards Institution
CBD: Cardanol Biodiesel
CGCA: Canopy Ground Cover Area
CI: Compression Ignition
CNSL: Cashew Nut Shell Liquid
CPO: Crude Palm Oil
CR: Compression Ratio
25D: 75:25 Ester/Diesel
DR-CNSL: Double Refined Cashew Nut Shell Liquid
DI: Direct Injection
DOC: Diesel Oxidation Catalysts
EU: European Union
EIA: Environment Impact Assessment
EPA: Environment Protection Agency (US)
FCFA: Free Cash Flow Annual
FFA: Free Fatty Acids
FAME: Fatty Acid Methyl Ester
FAEE: Fatty Acid Ethyl Ester
GC: Gas Chromatography
GPC: Gas Pressure Chromatography
HPLC: High Performance (pressure) Liquid Chromatography
IDI: Indirect Injection
IEA: International Energy Agency
IT: Injection Timing
IC: Internal Combustion
IP: Injection Pressure
IR: Infra Red
MT: Million Tons
NAA: Naphthalene Acetic Acid
NPV: Net Present Value
NMR: Nuclear Magnetic Resonance
NRI: National Research Institute
PAH: Polycyclic Aromatic Hydrocarbons
POD: Palm Oil Diesel

$O_{2:}$ Oxygen
Pv : Vapor Pressure
POD: Palm Oil Diesel
RPM: Revolution Per Minute
SOF: Soluble Organic Fraction
SO_x: Oxides of Sulphur
TPI: Tropical Products Institute
TLC: Thin Layer Chromatography
VOs: Vegetable oils
VCR: Variable Compression Ratio
WAF: Waste Animal Fat
WFO: Waste Frying Oil

Nomenclature

BTE: Brake Thermal Efficiency [in percentage]
B.S.E.C: Brake Specific Energy Consumption [in kJ/kW-hr]
BTE: Brake Thermal Efficiency [in percentage]
B P: Brake Power [in kW]
bp : Boiling Point [in ^{o}C]
CV: Calorific Value (kJ/kg)
CO: Carbon Monoxide [in percentage]
CO2: Carbon Dioxide[in percentage]
EGT: Exhaust Gas Temperature at Engine [in ^{o}C]
HC: Hydrocarbons [in percentage]
KV: Kinematic Viscosity [in mm^{2}/sec]
NOx: Nitrogen Oxides [in percentage]
PM: Particulate Matter [in ppm]
vppm: parts per million by volume
UBHC: Unburnt Hydrocarbons [in percentage]

CHAPTER-1

INTRODUCTION

1. INTRODUCTION

In today’s world majority of automotive and transportation vehicles are powered by compression ignition engines, which use diesel as fuel. Pollution being the main concern today extensive research has proved that exhaust emissions cause considerable environmental pollution, diminished air quality, acidic precipitation, toxic chemical transport and climate change impacts. Petro diesels are not evenly distributed on the globe, which means that they must be transported over greater distances from source to market; This increases the potential for soil and water contamination at any point in extraction, bulk transport, refining, distribution, storage and supply.

Self-reliance in energy is vital for the economic development of a nation [54]. The needs to search for alternative sources of energy which are renewable and eco-friendly assume top priority in view of the uncertain supplies and frequent price hikes of fossil fuels in the international market. There are many tree species which bear seeds rich in oil having properties of an excellent fuel and which can be processed into a diesel substitute. Of these some important varieties are Pongamia, Jatropha, Neem, Mahua, Simarouba, Sal, Undi, Pilu etc.. Non-edible oils that can be used to produce bio-fuels are gaining worldwide acceptance as one of the comprehensive solutions for problems of environmental degradation, energy security, restricting imports, rural employment and agricultural economy. “Bio-fuels are fuels produced by a number of chemical / biological processes from biological materials like plants, agricultural wastes etc. Being sourced from trees already existing and to be further propagated, bio-fuel is a source of renewable energy” [54]. Bio-diesel can be used as a pure fuel or blended with petroleum diesel depending on the economics and emissions.

It has been reported that [5] in diesel engines, vegetable oils can be used as fuel, straight as well as in blends with diesel. It is evident that there are various problems associated with vegetable oils being used as fuel in compression ignition engines, mainly caused by their high viscosity. The high viscosity is due to the large molecular mass and chemical structure of vegetable oils, which, in turn, leads the problems in pumping, combustion and atomization in the injector system of a diesel engine. Due to the high viscosity, vegetable oils normally introduce the development of gumming, the formation of injector deposits, ring sticking as well as incompatibility with conventional lubricating oils in long-term operations.

1.1 WORLD BIOFUEL SCENARIO

Renewable resources are more evenly distributed than fossil and nuclear resources and energy growths from renewable resources are more than three orders of magnitude higher than current global energy use. Today’s energy system is unsustainable because of equity issues as well as environmental, economic, and geopolitical concerns that have implications far into the future. According to International Energy Agency (IEA), scenarios developed for the US and the EU indicate that near term targets of up to 6% displacement of petroleum fuels with biofuels appear feasible using conventional biofuels, given available crop land. A 5% displacement of diesel requires 13% of US cropland [11], 15% in the EU. The dwindling fossil fuel sources and the increasing dependency of the US on imported crude oil have led to a major interest in expanding the use of bio-energy. The recent commitment by the US government to increase bio-energy three-fold in 10 years has added impetus to the search for viable biofuels. The EU have also adopted a proposal for a directive on the promotion of the use of bio-fuels with measures ensuring that bio-fuels account for at least 2% of the market for gasoline and diesel sold as transport fuel by the end of 2005, increasing in stages to a minimum of 5.75% by the end of 2010 [8,11,50].

1.2 INDIAN BIOFUEL SCENARIO

India, like most of the developing countries is highly dependent on imported oil (70% of its requirement) and petroleum products are causing heavy burden on foreign exchange since 2003. The demand for the crude oil has increased dramatically and country’s cost for import of crude oil has increased substantially. India, facing the challenge of meeting a rapidly increasing demand for energy, ranks sixth in the world in terms of energy demand. Its economy is projected to grow 7%-8% over the next two decades and there will be a substantial increase in demand for oil to manage transportation and also to meet various other energy needs [23]. The domestic production of crude oil has stagnated, while the demand has been rising at a rapid rate, resulting in increased crude oil imports. Based on the progress visualized for the nation during the next two decades, the power generating capacity has to increase to

400,000 MW by the year 2030 from the current 130,000MW in India [11]. With steady increase in demand, it is expected that the total crude oil resources may be sufficient only for the next 30-40 years. During 2004-05, the country imported 95.86 million tons (MT) of crude oil valued at US$ 26 billion and during 2005-06, the country imported 98.26 MT valued at US $ 41 billion. The Indian economy is expected to grow at a rate of over 6 % per annum and the petroleum imports are projected to rise to 166 MT by 2019 and 622 MT by 2047 [8].

Replacement of fossil fuels by liquid fuels produced from renewable source is a high priority goal in many countries world wide. It is driven by the aim of a secure and sustainable energy supply and is desired to diminish the green house effect. The transportation sector is dependent mainly on the diesel fuel. In the year 2004-2005, 121500 crores (27 million $) worth fuel was imported. From the Table 1.1 production of crude oil in India is almost constant from past 5 years and is only 20%-25% of imported crude oil. During 2006-2007, 147 million tons of crude oil was imported [11, 50, 35, and 55]

Table 1.1: Production and import of crude oil in India

Year	Production Million Tons	Import Million Tons	Total Million Tons	Import % of Total
1971	6.8	11.7	18.5	63
1981	10.5	16.2	26.7	61
1991	33	20.7	53.7	39
2000	32	57.9	89.9	64
2003-04	33.4	90.4	123.8	73
2004-05	33.4	100	133.4	75
2006-07	33.4	147	180.4	81.7

Under technology mission of 1986 on oil seeds starting from mere 11 billion tons during 1986-87, India attained 25 billion tons in 1996-97. The Table 1.2 illustrates that India occupies a prominent position with regard to area under cultivation, standing second in the world. However the yield is lowest among all other countries. The wasteland (70 million hectare) in the country can be made to become green and yield oil and bio-residues for various uses.

Table 1.2: Cultivated areas of oil seed plants

Country	Oilseed Million hectare	% world oil seed area	Yield Tons/ hectare
USA	35.98	18.94	2.1
India	**32**	**16.84**	**0.89**
China	28.01	14.74	1.84
Brazil	22.51	11.85	2.45
Argentina	16.54	8.55	2.32
Canada	5.36	3.09	1.55
Others	13.05	6.85	---------

Growing these oil bearing plants on wastelands, as avenue trees and in the back yards all over the nation will improve the availability of these oil seeds. Further, local growth associated in crushing and marketing encourages the entrepreneurs to start small industries to produce raw or finished goods. This is one of the factors that contribute to the concept of sustainable rural areas where environment and people are independent and India could be a world lender in supply of oil. Since edible oils like sunflower, saffola, soyabean etc. are in great demand for domestic consumption, in India non edible seed crops like madhuca indica(Mahua), pongamia pinnata (honge), jatropha curcus (ratanjot, jatropha) etc. can provide oil, which can be developed as biofuel.

1.3 POTENTIAL FOR USE OF TREE BASED SEEDS

We, in India have a well established collection and marketing network for non-edible oils, going back to the Vedic days, for use as fuel for lighting lamps. There are more than 300 different species of trees, which produce oil-bearing seeds and therefore we do not have to pursue any monoculture to obtain them. Most of these trees are wild and therefore once established will look after themselves. At commonly used densities of more than 100 trees per hectare, many of these trees yield 10 to 15 tons of seeds per hectare on maturing. Since 15 to 20 year old trees use soil to more than 10meter depth (unlike agricultural crops which use only 0.15 meter of top soil), both the survivability during dry periods and annual output per hectare are better than what could be obtained from many agricultural crops. There is also no possibility of total yield failure with trees in any year. These are well documented [11, 35, and 43].

Most tree-based oil seeds yield about 25% oil and 70% cake, considering 5% losses in the process of oil extraction using expellers. This technology is well established in our country. The cake has multiple uses but if it becomes available in large quantities, it probably could be used best in industrial fomenters to produce biogas (methane) and the sludge produced thereof can be used as quality fertilizer. This use can also be extended on a small scale to the villages for local use. Due to wide variations in climate, soil conditions and competing uses for land, different nations have to consider different vegetable oils as potential fuels. For example, Malaysia, a leading producer of palm oil is experimenting with palm oil and its derivatives as fuels for engines. In India, madhuca indica (mahua), pongamia pinnata (honge) are considered to be most suitable for making biofuel [8, 35].

The American Society for Testing and Materials (ASTM) defines biodiesel fuel as mono alkyl esters of long chain fatty acids derived from a renewable lipid feedstock, such as vegetable oil or animal fat. ‘‘Bio’’ represents its renewable and biological source in contrast to traditional petroleum-based diesel fuel; ‘‘diesel’’ refers to its use in diesel engines [10]. As an alternative fuel, biodiesel can be used in neat form or mixed with petroleum-based diesel. Biodiesel, as an alternative fuel, has many merits. It is derived from a renewable, domestic resource, thereby relieving reliance on petroleum fuel imports. It is biodegradable and non-toxic. Compared to petroleum-based diesel, biodiesel has a more favorable combustion emission profile, such as low emissions of carbon monoxide, particulate matter and unburned hydrocarbons. Carbon dioxide produced by combustion of biodiesel can be recycled by photosynthesis, thereby minimizing the impact of biodiesel combustion on the greenhouse effect. Biodiesel has a relatively high flash point (150^{o}C), which makes it less volatile and safer to transport or handle than petroleum diesel. It provides lubricating properties that can reduce engine wear and extend engine life. In brief, these merits of biodiesel make it a good alternative to petroleum based fuel and have led to its use in many countries, especially in environmentally sensitive areas. The most common way to produce biodiesel is by transesterification, which refers to a catalyzed chemical reaction involving vegetable oil and an alcohol to yield fatty acid alkyl esters (i.e., biodiesel) and glycerol. Triacylglycerols (triglycerides), as the main component of vegetable oil, consist of three long chain fatty acids esterified to a glycerol back bone. When triacylglycerols react with an alcohol (e.g., methanol), the three fatty acid chains are released from the glycerol skeleton and combine with the alcohol to yield fatty acid alkyl esters (e.g., fatty acid methyl esters or FAME). Glycerol is produced as a by-product.

Transesterification of vegetable oils with simple alcohol has long been a preferred method for producing biodiesel fuel [21]. Generally speaking, there are two methods of transesterification reaction. One is the method using a catalyst and the other is without the help of a catalyst. The former method has a long story of development and now biodiesel fuel produced by this method is in the market in some countries such as North America, Japan and some west European countries. However, there are at least two problems associated with this process; the process is relatively time consuming and purification of the product for catalyst and saponified products are necessary. The first problem due to the two-phase nature of vegetable oil/methanol mixture requires vigorous stirring to proceed in the transesterification reaction.

1.4 Types of Emissions [10]

There are five different types of emissions from the diesel engine exhaust, namely: NOx (Nitrogen oxides), PM (particulate matter), HC (hydrocarbons), CO (carbon monoxide), and CO_2 (Carbon dioxide). While CO_2 is not a hazardous air toxin, it is considered a greenhouse gas emission causing global warming and, in some cases, may be capable of generating emissions credits.

1.4.1 NOx Emissions

Nitrogen oxides (NOx) is the generic term for a group of highly reactive gases containing nitrogen and oxygen in varying amounts, including nitric oxide (NO), nitrous oxide (N_2O), nitrates (NO_3), and nitrogen dioxide (NO_2). NOx and volatile organic compounds, in the presence of hot, stagnant air and sunlight, convert to ozone. NOx are classified as hazardous airborne toxins because of their deleterious health and environmental effects. The U.S. Environmental Protection Agency (EPA) has noted that NOx is a major cause of ground-level ozone (a.k.a. smog), acid rain, respiratory disease (emphysema and bronchitis), water quality determination and global warming.

1.4.2 PM Emissions

Particulate matter (PM) is a generic term used for a type of airborne pollution which consists of varying mixtures, complexity and sizes of particles. PM is problematic because it compounds respiratory problems, such as asthma and cardiopulmonary disease. The American Lung Association reports that high concentrations and/or specific types of particles have been found to present a serious danger to human health. There are two types of regulated PM: PM2.5 and PM10. PM2.5 is a particulate matter of 2.5 micrometers or less in diameter and PM10 is a particulate matter of 10 micrometers or less in diameter. Both PM2.5 and PM10 are byproducts of internal combustion engines. There are two major differences between PM2.5 and PM10. First, the size contributes to greater health risks because larger particles can be inhaled and accumulated in the respiratory system. Secondly, in contrast to PM2.5, PM10 easily reacts with chemicals such as SO_2, NOx, and volatile organic compounds (VOCs). All of these chemical reactions can result in smog.

1.4.3 HC Emissions

The Agency for Toxic Substances and Disease Registry reports that hydrocarbons (HC) “enter the air mostly as releases from volcanoes, forest fires, burning coal, and automobile exhaust”. A 1999 EPA study estimates that on-road vehicle sources are responsible for 29 percent of the total emission of HC. Mobile sources release two types of regulated HC measured as speciated hydrocarbons (C1-C22) and a subset of known or suspected carcinogenic compounds titled polycyclic aromatic hydrocarbons (PAH).

1.4.4 CO Emissions

Carbon monoxide (CO) is produced from incomplete combustion whenever any carbon fuel, such as gas, oil, kerosene, wood, or charcoal is burned. Unlike many gases, CO has no odor, color, or taste, and it does not cause skin irritation. According to the Centers for Disease Control and Prevention¸ red blood cells can attach themselves to CO at a quicker rate than to oxygen. If there is a large quantity of CO in the air, the red blood cell may replace oxygen with CO, leading to possible tissue damage, carbon monoxide poisoning or death. As CO levels increase and remain above 70 parts per million (ppm), symptoms may become more noticeable (headache, fatigue, nausea). As CO levels increase above 150 to 200 ppm, disorientation, unconsciousness, and death are possible.

1.4.5 CO_2 Emissions

Carbon dioxide is a naturally occurring gas that is linked to global warming. It is also released into the atmosphere by human activity, such as when solid waste, fossil fuels (oil, natural gas, and coal), and wood and wood products are burned. Carbon dioxide by itself is not considered to be a toxin. However, any impacts on global climate could cause health problems.

1.5 Emission Control Technologies for Off-Road Diesel engines in Mining area

Some of the emission control technologies used in off-road mining area are listed below [66].

- Diesel Oxidation Catalysts
- Particulate Filters
- Lean NOx Catalysts
- Exhaust Gas Recirculation (EGR)

1.5.1 Diesel Oxidation Catalysts

In most applications, a diesel oxidation catalyst consists of a stainless steel canister that contains a honeycomb structure called a substrate or catalyst support. There are no moving parts, just large amounts of interior surface area. The interior surfaces are coated with catalytic metals such as platinum or palladium. It is called an oxidation catalyst because the device converts exhaust gas pollutants into harmless gases by means of chemical oxidation. In the case of diesel exhaust, the catalyst oxidizes CO, HC, and the liquid hydrocarbons adsorbed on carbon particles. In the field of mobile source emission control, liquid hydrocarbons adsorbed on the carbon particles in engine exhaust are referred to as the soluble organic fraction (SOF) -- the soluble part of the particulate matter in the exhaust. Diesel oxidation catalysts are efficient at converting the soluble organic fraction of diesel particulate matter into carbon dioxide and water. DOCs can typically achieve 25 to 40% particulate reduction by simply burning the SOF component of particulate matter.

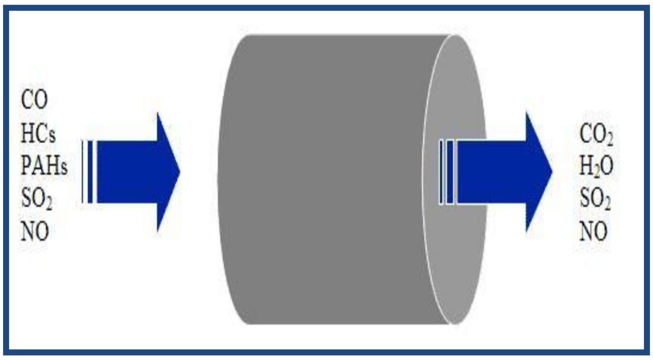


Figure.1.1 Diesel Oxidation Catalysts

1.5.2 Lean NOx Catalysts

A lean NOx catalyst often includes a porous material made of zeolite (a micro-porous material with a highly ordered channel structure), along with either a precious metal or base metal catalyst. The zeolites provide microscopic sites that are fuel/hydrocarbon rich where reduction reactions can take place. Without the added fuel and catalyst, reduction reactions that convert NOx to N2 would not take place because of excess oxygen present in the exhaust. Currently, peak NOx conversion efficiencies typically are around 10 to 30 percent (at reasonable levels of diesel fuel reductant consumption).

Figure.1.2 Lean NOx Catalysts

1.5.3 Particulate Filters

Diesel particulate filters remove particulate matter found in diesel exhaust by filtering exhaust from the engine. In order to meet the stringent particulate emissions that are required for diesel light duty vehicles starting with the 2007 model, the highest efficiency particulate filter is required. These are commonly made from ceramic materials such as cordierite, aluminum titanate, mullite or silicon carbide. The basis for the design of wall flow filters is a honeycomb structure with alternate channels plugged at opposite ends. As the gasses pass into the open end of a channel, the plug at the opposite end forces the gasses through the porous wall of the honeycomb channel and out through the neighboring channel. The ultrafine porous structure of the channel walls results in greater than 90% collection efficiencies of these filters. Wall flow filters capture particulate matter by interception and impaction of the solid particles across the porous wall. The exhaust gas is allowed to pass through in order to maintain low pressure drop.

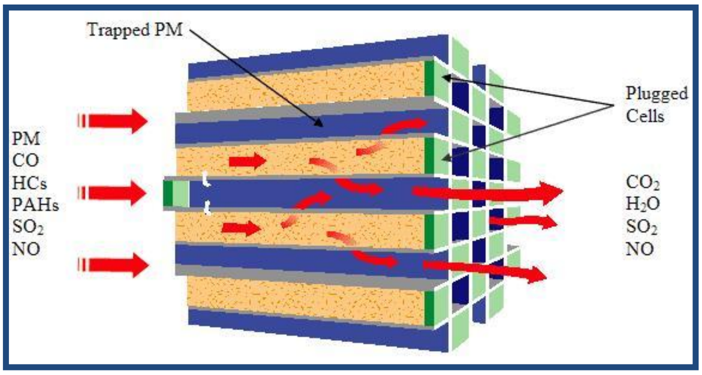


Figure 1.3 Diesel Particulate Filters

1.5.4 Low-pressure EGR + DPF

Approaches aimed at reducing cold start emissions involve retarding the ignition timing to allow some hydrocarbons to pass through in the exhaust and light off the catalyst sooner. Variable valve timing (VVT) is being used to introduce some fraction of exhaust gas into the combustion process and reduce HC and NOx emissions.

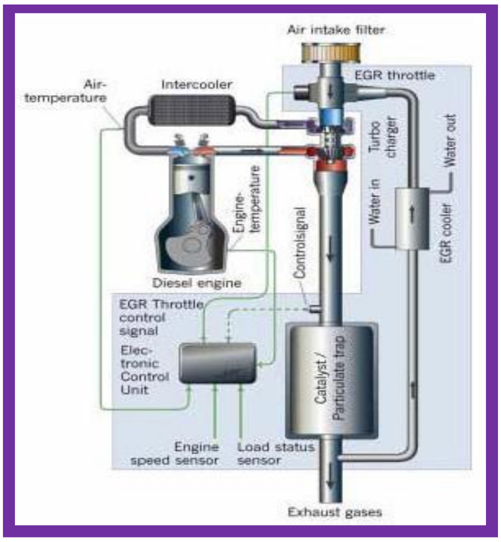


Figure 1.4 Low-pressure EGR + DPF

On clean diesel engines, Exhaust Gas Recirculation (EGR) is used to dilute intake air with some fraction of exhaust gas to lower the combustion temperatures resulting in lower engine out NOx emissions. Direct injection of fuel into the cylinders rather than port injection has allowed better control of the air-fuel ratio during combustion and resulted in better fuel utilization. Improved turbulence and mixing in the intake port of some low emission engines have resulted in 24% fuel savings. Clean diesel engines have benefited significantly from common rail fuel injection which allows for electronically controlled injection at very high pressures. Through the use of pilot and retarded injection strategies or in combination with injection rate shaping clean diesels have achieved significant reduction in NOx over conventional diesel injection such as pipe-line or unit injection. Common rail and electronic injection control is very effective in carefully controlling post injection of fuel making it suitable for use with emission control devices such as particulate filters, NOx adsorbers and lean NOx catalysts requiring brief periods of fuel rich exhaust to facilitate regeneration of the catalyst or filter.

Keeping in view the plight of the energy crisis, I have experimented on and have used cardanol biodiesel and its blends with diesel for investigation in single cylinder, VCR and Twin cylinder diesel engines.

The performance of a various diesel engines and emissions were studied at variable loads, corresponding to the load at maximum power at an average speed of 1500 rpm. After the engine reached the stabilized working condition, load applied, fuel consumption, brake power and exhaust temperature were measured from which brake specific fuel consumption, brake specific energy consumption and thermal efficiency were computed. The emissions such as CO, HC, and NOx were measured using an automotive emission analyzer QRO–402 exhaust gas analyzer and A DELTA 1600-L of MRU make exhaust gas analyzer. These performances and emission characteristics for different blends are compared with the result of baseline diesel. Each reading was obtained thrice to obtain a reasonable value.

1.6 ORGANIZATION OF THE THESIS

The first introduction chapter, introduce the world biofuel scenario, Indian biofuel scenario, potential for use of tree based seeds, types of emissions, emission control technologies for off-road diesel, engines in mining area, diesel oxidation catalysts, lean NOx catalysts, particulate filters low-pressure EGR & DPF.

The chapter 2 introduces an overview of the main literature survey and subjects related to this work. A brief historical background on the use of various kinds of vegetable oil and their derivatives as fuel in diesel engines, and their effects on combustion in diesel engine discussed. Performance and emission characteristics of preheated vegetable oil, and their blends with diesel on diesel engines are presented.

Introduction to diesel fuel & its classification, biodiesel, bio diesel manufacture, biodiesel fuel properties, highlights of the fuel properties and highlights of the literature. Section 2.7 presents the Cardanol oil as alternative fuel ,Cashew agronomy, sections and breeding, fruit set and fruit development, cashew nut processing, cashew nut shell liquid (CNSL) and its extraction, extraction of cardanol and cardol from CNSL, reason for using cardanol oil as alternative fuel & the chapter 2, ends with objectives of present work.

Detailed information on experimental set up of single, VCR & twin cylinder engines with instrumentation, and experimental procedure for all engines are presented in Chapter 3.

Chapter 4 presents the results and discussions of single, VCR & twin cylinder engines by using CBD blends. Performance and emission characteristics cardanol biodiesel blends with diesel in terms of BTE, BSFC, BSEC, CO, HC, and NOx were evaluated and results were compared with that of diesel.

The experimental investigations have been carried out to evaluate the effect of different blends against the various PE characteristics in single and multi-cylinder engines. Section 4.4, 4.5 & 4.6 covers the details of results and discussions of single cylinder, VCR & twin cylinder diesel engines respectively.

The chapter 5 presents the results and discussions of all the three engines at 20% CBD volumetric blends; considering the design aspects of the stationary diesel engine, and the regulations from our government that to use only 20% blend along with regular diesel fuel [73, 74]. This chapter presents the results and discussions of all the three engines at 20% blends.

Finally, conclusions and scope for future work were presented in Chapter 6.

CHAPTER-2

LITERATURE REVIEW

2.1 PREVIOUS RESEARCH WORKS

Diesel fuel is the single largest source for power vehicles both in transportation and agricultural sectors. With the increasing demand on the use of fossil fuels, a stronger threat to clean environment is being posed as the burning of fossil fuels is associated with emissions like CO_2, CO, SO_x, NO_x and PM (particulate matter), which are currently the dominant global source of emissions. These emissions are major causes of air pollution and hence of the environment.

This chapter presents the detailed literature review on the vegetable oils and their derivatives as an alternative fuel for CI engines. A brief historical background is followed by, the investigation of properties of vegetable oils and their blends, performance and exhaust emission characteristics of neat vegetable oils and their blends with diesel. Brief discussions on performance and exhaust emissions characteristics of biodiesel and its blends with diesel, on various diesel engines were studied. In addition, a brief literature review is presented on the effect of transesterification and blending of non-edible vegetable oils, diesel fuel and its classifications, biodiesel and its production, Cardanol oil as alternative fuel, extraction of cardanol and cardol from cnsl the chapter ends with a note on the objectives of present work.

2.2 HISTORICAL BACKGROUND

The use of vegetable oils, such as palm, soyabean, sunflower, peanut, and olive oil, as alternative fuels for diesel engines dates back almost to nine decades, but due to the rapid decline in crude oil reserves, it is again being promoted in many countries. Depending upon the climate and soil conditions, different countries are looking for different types of vegetable oils as substitutes for diesel fuels. For example, soyabean oil in the US, rapeseed and sunflower oils in Europe, palm oil in South-east Asia (mainly Malaysia and Indonesia) and coconut oil in the Philippines are being considered.

The concept of using vegetable oil as fuel for diesel engines is nothing new. Dr.Rudolph Diesel first developed the diesel engine in 1895 with an intention of running it on a variety of fuels, including vegetable oil. Diesel demonstrated his engine at the Paris Exposition of 1911 using peanut oil fuel. In 1911, he stated; “The diesel engine can be fed with vegetable oils and will help considerably in the development of agriculture of the countries which use it". In 1912, Diesel said; "The use of vegetable oils for engine fuels may seem to be insignificant today. Such oils may become, in course of time, as important as petroleum and the coal tar products of the present time". The interest in using vegetable oils as alternative fuels originated within the agricultural community as a fuel for agricultural tractors and equipments.

In India extensive, research has been carried out both on stationary & mobile vehicles for use of biodiesel as a fuel. The biodiesel in blend with diesel & various other additives, bio fuel dual fuel mode& with L.P.G & C.N.G has been tried extensively on stationary CI engines. Work has been carried out in studying the feasibility of biodiesel in transport buses & trains.

It is heartening to note that serious initiatives are being made in India by Government agencies, Universities, Research Institutions and Private organizations towards these efforts [54]. For example, The Southern Railways, KSRTC, Ford automobiles etc have intensely worked on physical and chemical variations of oils from different species and have given a positive report on the impact of using biodiesel on the efficiency of the engines and environment. Scientists and engineers have worked in good co-ordination and have arrived at a dozen oil-yielding crop species that can be cultivated on a commercial scale for the production of biodiesel.

At international level, experiments have been carried out on stationary engines using biofuel mode from some of the edible oils like Saffola, Soyabean, sunflower etc. In addition, non-edible oil like jojoba also been tried out.

2.3 VEGETABLE OILS AND THEIR BLENDS

Keeping in view the potential properties of vegetable oils as fuel, number of investigations at National and International level have been made.

A large number of experiments were carried out with vegetable oils as a replacement of fuel for I.C. engines by researchers from various parts of the world. Most of these experiments were reported from U.S., Europe, India, Malaysia and Germany.

2.3.1 Required characteristics of vegetable oil as fuel

Vegetable oils provide diesel engine performance similar to that obtained with diesel oil as per the experiments carried out by the research workers. The following are the important characteristics of good vegetable fuels required to substitute diesel oil [12].

- ***Ignition quality:*** Satisfactory diesel combustion demands self-ignition of the fuel as it is sprayed near the TDC into the hot, swirling compressed cylinder gas. Long ignition delay is not acceptable as it leads to knocking. Therefore, cetane number of the substitute fuel should be high enough, i.e., in between 40 and 60.
- ***Viscosity:*** Too low viscosity can lead to excessive internal pump leakage whereas high viscosity can increase system pressure to unacceptable levels and will affect injection during the spray atomization.
- ***Heating value:*** Although, the diesel combustion system can accept wide variations in heating value, practical systems are most suitable when calorific value of fuel is high. This helps to reduce the quantity handled and to maximize equipment operating range. It is always desirable for vegetable fuels to have calorific value nearer to that of diesel oil.
- ***Pour Point, Cloud Point and Flash Point:*** First two properties are important for cold weather operation. For satisfactory working the values of both should be well below freezing point of the oil used. Flash point is important from safety viewpoint and this temperature should be as high as the practical value.
- ***Sulfur, Carbon Residue and Ash:*** These properties are responsible for corrosion and forming the residue on the engine parts which will affect the engine life. These values should be as small as possible. Practical values are 0.5% sulfur, 0.27% Carbon residue and 0.01% ash.

- ***Miscibility with diesel:*** Vegetable oil should mix with diesel at various proportions and kept untouched for 24 hours.
- ***Aniline point:*** Aniline point is the lowest temperature at which the oil is completely miscible with an equal volume of aniline. For a good quality of diesel, aniline point is greater than 21^{o} C.

Ayhan Demirbas et al. [5] studied the biodiesel from vegetable oils via transesterifications in supercritical methanol. The author investigated the transesterification of six vegetable oil samples by using methanol without using any catalyst, and mentioned some standards for testing biodiesel fuels. Vegetable oil fuels have not been acceptable because they were more expensive than petroleum fuels. With recent increases in petroleum prices and uncertainties concerning petroleum availability, there is renewed interest in vegetable oil fuels for Diesel engines. Dilution of oils with solvents and micro emulsions of vegetable oils lowers the viscosity, but some engine performance problems still exist. The purpose of the transesterification process is to lower the viscosity of the oil. Pyrolysis produces more bio gasoline than bio diesel fuel. Soap pyrolysis products of vegetable oils can be used as alternative Diesel engine fuel. Methyl and ethyl esters of vegetable oils have several outstanding advantages among other new renewable and clean engine fuel alternatives. The main factors affecting transesterification are the molar ratio of glycerides to alcohol, catalyst, reaction temperature and pressure, reaction time and the contents of free fatty acids and water in oils. The commonly accepted molar ratios of alcohol to glycerides are 6:1–30:1.

Sharanappa Godiganur, et al. [62] studied, “6BTA 5.9 G2-1Cummins engine performance and emission tests using methyl ester mahua (madhuca indica) oil/diesel blends”.The basic composition of any vegetable oil is triglyceride, which is the ester of three fatty acids and glycerol. Vegetable oils have to undergo the process of transesterification to be usable in IC engines. Biodiesel is an alternative fuel, which has a correlation with sustainable development, energy conservation, management, efficiency and environmental preservation. In transesterification, mahua oil was chemically reacted with an alcohol in the presence of a catalyst to produce vegetable oil esters.Glyserol is produced as a by-product of reaction.

The mixture is stirred continuously and then allowed to settle under gravity in a separating funnel. Two distinct layers were formed after gravity settling for 24h.The upper layer was ester and the lower layer was of glycerol. The lower layer was separated out. The separated ester was mixed with some warm water(around 10% volume of ester) to remove the catalyst present in the ester and was allowed to settle under gravity for another 24h.The ester was then blended with mineral diesel to be used in CI engine.

The present study was carried out to investigate the performance and emission characteristics of methyl ester of mahua oil and it blends in a Cummins 6 BTA 5.9 G2-1,158 HP, and turbo-charged engine. The values were compared with baseline data of diesel fuel. The engine was coupled to a POWERICA A.C. generator set and loaded by electrical resistance to apply different engine loads. The voltage, current and power developed by the engine were directly displayed on the control panel. Based on the results of the study, the fuel properties of mahua biodiesel were found to be within limits except for the calorific value; all other fuel properties of mahua biodiesel were found to be higher as compared to diesel. The brake specific fuel consumption increase and brake thermal efficiency decreased with increase in the proportion of biodiesel in the blends. A reverse trend was observed with increase in engine load. The amount of CO and HC in exhaust emission reduced, whereas NOx increased with increase in percentage of mahua biodiesel in the blends. However, the level of emission increased with increase in engine load for all fuels tested. The performance and emission parameters of different blends were better compare to diesel. The emission levels of CO and HC in heavy duty engines were less compared with small engines. From these findings, it is concluded that mahua biodiesel could be safety blended with diesel up to 20% without significantly affecting the engine performance (BSFC, BSEC, and EGT) and emissions (CO, HC and NOx) and thus could be a suitable alternative fuel for heavy-duty engines.

Fernando neto da Silva et al. [14] investigated the technical feasibility assessment of oleic sunflower methyl ester utilization in diesel bus engines. He used oleic sunflower methyl ester (SME) blended with diesel fuel in proportion up to 30% in unmodified diesel bus engine. The results include evaluation of engine performance and fuel consumption and gaseous concentrations (CO & NOx) in the exhaust gas. The exhaust gas opacity while using diesel/SME blends and diesel fuel was also compared. The collected data shows that oleic SME utilization did not lead to deterioration of engine performance or to an increase in fuel consumption and significant increase of CO & NOx concentrations in the exhaust gas derived from SME utilization were not detected. The smoke opacity was slightly reduced when SME was used in the proportion of 30%.The experiment testing seems to indicate that oleic SME is a suitable replacement for diesel fuel and can be used safely in CI engines in proportion as high as 30%.

K.Pramanik et al. [26] studied the properties and use of jatropha curcas oil and diesel fuel blends. In CI engine the blends of varying proportions of jatropha curcas oil and diesel fuel were prepared, analyzed and compared with diesel fuel; the effect of temperature on the viscosity of biodiesel and jatropha oil was also studied. The performance of the engine using blends and jatropha oil was evaluated in a single cylinder CI engine and compared with the performance obtained with diesel. The effect of temperature on the viscosity of biodiesel and jatropha oil was also studied. Significant improvement in engine performance was observed compare to vegetable oil alone. Acceptable thermal efficiencies of the engine were obtained with blends containing up to 50%by volume of jatropha oil.

Gurpreet Singh et al. [21] studied performance emission characteristics of heavy-duty engine combustion. The objectives of the study were to describe the research efforts in diesel engine combustion at Sandia National Laboratories Combustion Research Facility. There are four diesel engine experiments namely : i) a one-cylinder version of a Cummins heavy-duty engine, ii) a diesel simulation facility, iii) a one-cylinder Caterpillar engine to evaluate combustion of alternative fuels, and iv) a homogeneous-charge, compression-ignition (HCCI) engine facility, to study the effects of injection timing and diluents addition on late-combustion soot burnout, diesel-spray ignition and premixed-burn behavior, a comparison of the combustion characteristics of M85 (a mixture of 85% methanol and 15% gasoline) and DF2 (#2 diesel reference fuel), and a description of our HCCI experimental program and modeling work.

Gemma Vicente et al. [17] studied, “Integrated bio diesel production: a comparison of different homogeneous Catalysts systems”. A comparison is made of different basic catalysts i.e. sodium methoxide, potassium methoxide, sodium hydroxide and potassium hydroxide for methanolysis of sunflower oil. All the reactions were carried out under the same experimental conditions in a batch stirred reactor and the subsequent separation and purification stages in a decanter. The analytical methods included gas chromatography and the determination of fat and oil conventional parameters. The bio diesel purity was near 100 wt. % for all catalysts. However, near 100 wt. % biodiesel yields were only obtained with the methoxide catalysts. According to the material balance of the process, yield losses were due to triglyceride saponification and methyl ester dissolution in glycerol. Obtained biodiesel met the measured specifications, except for the iodine value, according to the German and EU draft standards. Although all the transesterification reactions were quite rapid and the biodiesel layers achieved nearly 100% methyl ester concentrations, the reactions using sodium hydroxide turned out to be the fastest.

S. Kalligeros, et al [56] studied “An investigation of using biodiesel/marine diesel blends on the performance of a stationary diesel engine”. Vegetable oils are produced from numerous oil seed crops. While all vegetable oils have high-energy content, most require some processing to assure safe use in internal combustion engines. Some of these oils have already been evaluated as substitutes for diesel fuels. With the exception of rapeseed oil which is the principal raw material for biodiesel fatty acid methyl esters, sunflower oil, corn oil and olive oil, which are abundant in Southern Europe, along with some wastes, such as used frying oils, appear to be attractive candidates for biodiesel production. In this paper, fuel consumption and exhaust emissions measurements from a single cylinder stationary diesel engine are described. The engine was fueled with pure marine diesel fuel and blends containing two types of biodiesel, at proportions up to 50%. The two types of biodiesel appeared to have equal performance, and irrespective of the raw material used for their production, their addition to the marine diesel fuel improved the particulate matter, unburned hydrocarbons, nitrogen oxide and carbon monoxide emissions. The substitution of marine diesel with biodiesel produced from sunflower oil and olive oil leads only to positive outcomes. These two types of biodiesel caused hydrocarbon and nitrogen oxide emissions and resulted in a slight increase of the volumetric fuel consumption. The strong advantage of the use of biodiesel seems to be the fact that independently on the raw material used for the production; its addition into the marine fuel improves all the emissions and especially particulate matter that comprises a serious problem for the diesel and marine diesel engines, especially in polluted areas such as ports and beaches.

M. Senthil Kumar et al. [32] studied, "An experimental comparison of methods to use methanol and Jatropha oil in a compression ignition engine". In this work various methods of using vegetable oil (Jatropha oil) and methanol such as blending, transesterification and dual fuel operation were studied experimentally. A single cylinder direct injection diesel engine was used for this work. Tests were done at a constant speed of 1500 rev.min^{-1} at varying power outputs. In dual fuel operation the methanol-Jatropha oil ratio was maintained at 3:7 on the volume basis. This is close to the fraction of methanol used to prepare the ester with Jatropha oil. Brake thermal efficiency was better in the dual fuel operation and with the methyl ester of Jatropha oil as compared to the blends. It increased from 27.4% with neat Jatropha oil to a maximum of 29% with the methyl ester and 28.7% in the dual fuel operation. Smoke was reduced by all methods for the sake of neat vegetable oil operation.

S.Sundarapandian et al. [58] studied, "Performance and Emission Analysis of Bio Diesel Operated CI Engine." A theoretical model was developed to evaluate the performance characteristics, combustion parameters and emissions of Vegetable oil esters like Jatropha, Mahua and Neem Oil esters. The predicted results of these fuels are compared with the experimental result of diesel fuel. From the results, it is found that the heat release and work done are reduced by about 4-8%with vegetable oil esters when compared to diesel. From the investigation, it is concluded that the performance of vegetable oil esters is good. Thus, the developed model is highly compatible for simulation work with biodiesel as an alternative fuel.

N. Stalin et al. [40] studied, "Performance test of IC engine using Karanja bio diesel blending with diesel". This paper presents a review of the alternative technological methods that could be used to produce this fuel. Biodiesel from karanja oil was produced by alkali catalyzed transesterification process. Performance of IC engine using karanja biodiesel blending with diesel and with various blending ratios has been evaluated. Parameters like speed of engine, fuel consumption and torque were measured at different loads for pure diesel and various combinations of dual fuel. Brake power, brake specific fuel consumption and brake thermal efficiency were calculated. The test results indicate that the dual fuel combination of B40 can be used in the diesel engines without making any engine modifications. Also the cost of dual fuel (B40) can be considerably less than that of pure diesel.

S. Win Lee et al. [57] studied, “Emission reduction potential from the combustion of soy methyl ester fuel blended with petroleum distillate fuel”. In this investigation, commercial No. 2 type heating oil and a B-20 blend has been used. The bio fuel blend was prepared using the same No. 2 fuel by mixing with 20% by volume of soybean methyl ester. The No. 2 oil is used as the reference or control fuel for the performance evaluation of the biofuel blend. The soy ester was produced in Canada using a proprietary process and was provided by a local fuel supplier. A typical combustion experiment commenced with pre-conditioning of the test room and fuel temperatures overnight, followed by calibration of emission analyzers in the morning. Examination and adjustment of boiler exhaust draft and fuel temperature were then made to attain optimum conditions. The selected burner combustion air initially optimized during combustion trials using No. 2 fuel was used without any additional adjustments for all final experiments. Multiple combustion runs were performed for both No. 2 fuel and B-20 blend under similar experimental conditions optimized for No. 2 fuel. It is important to note that no modifications to the burner, boiler or fuel delivery systems were made for burning B-20 blend. Replicate sets of fine particulate emission measurement were also conducted for both fuels under similar experimental conditions using the established source dilution sampling protocol. A typical particulate sampling experiment for a residential scale oil-fired appliance requires 6–20 h of continuous operation, depending on the emission rate of the fuel. After sampling, the filter samples were immediately stored and conditioned inside the temperature and humidity-controlled chamber. Typical analysis scheme for each PM fraction filter involves gravimetric determination of particle mass concentrations and quantification of three main PM constituents, namely, sulphates, carbons and trace elements. Each analysis was conducted using separate samples collected on individual filters that are of different materials. For example, characterization of PM2.5 fraction required four samples of different filter materials collected subsequently in the filter pack attached to the size selective cyclone. A simple mass balance for each particulate fraction was later calculated using the composite mass data from the three constituents analyzed.

Fuel properties of vegetable oils and modified hybrid fuels have been studied by many researchers [60, 44, 66, &52]. Compared to diesel, the vegetable oils, in general, have acceptable cetane number (35-45), high viscosity (>27cst), high carbon residue, high flash point (220-285 °C), cloud point (17-18) and pour points (-6 to -12° C), acceptable calorific value (88-94% of diesel), low sulphur content (<0.025) and contains gumming impurities. The major problem with direct use of vegetable oils as fuel into C1 engines is their high viscosity. It interfaces the fuel injection, atomization and contributes to incomplete combustion, nozzle clogging, excessive engine deposits, ring sticking, contamination of lubricating oil etc. The problem of higher viscosity of vegetable oils can be overcome to a great extent by various techniques, such as heating, dilution, emulsification and esterification as mentioned earlier.

2.3.2 Performance and exhaust emission characteristics

Engine performance is influenced by basic difference between diesel fuels and the viscosity, density and molecular oxygen content. The lower mass based heating values of the vegetable oils required larger mass of fuel flow to maintain constant energy input to the engine. C.I. engines burning regular petroleum products produce CO_2, CO, HC and other toxic emissions dangerous to human health, especially in highly populated urban areas. Vegetable oils offer a solution for environmental problems associated with these toxic emissions. The exhaust emissions of the diesel engines using vegetable oils deal with CO, HC and NOx emissions, soot and particulate emissions.

Sapuan et al. [60] reviewed the potential of palm oil as an alternative fuel in automotive and industrial diesel engines with respect to its performance and terminological, environmental, economic and social implications. They observed that performance and exhaust gas emissions using palm oil fuel and its blends with conventional diesel fuel in stationary diesel engines are comparable with those of conventional diesel fuel. The high fuel consumption of palm oil fuel and its blends will compensate for the lower heating values such that the engines consume an equal amount of energy. They have also observed that, palm oil fuel is environmentally friendly, does not affect engine and bearing components seriously, does not degrade lubricating oil and produces comparable amounts of carbon deposits.

Review of Babu et al. [6], aims to study the prospects and opportunities of introducing vegetable oils and their derivatives as fuels in diesel engines. Fuel related properties are reviewed and compared with conventional diesel fuel. The use of neat vegetable oil (edible and/or non edible), biodiesel and its blends in a diesel engine has been discussed. Performance and emission characteristics are highlighted. Current developments on the use of vegetable oils and its blends, biodiesel and its blends in diesel engines are examined.

In the experimental investigation of Pugazhvadivu et al. [49], waste frying oil, (WFO) a non edible vegetable oil was used as an alternative fuel for diesel engine. Preheating reduces the high viscosity of the waste frying oil and the effect of temperature on the viscosity of WFO was evaluated. The results reveals that, using preheated WFO, the BSEC and break thermal efficiency were improved. Exhaust emission such as CO and smoke were reduced considerably. Maximum reduction in CO and smoke emissions was obtained using WFO (135°C) compared to WFO (75°C).

Bari et al. [7] studied the effect of preheating of crude palm oil (CPO) on injection system, performance and emission of diesel engine. It was observed that heating of fuel up to 100°C had no adverse effects on the fuel injection system and performance of CPO as a fuel was comparable to that of diesel. Comparing CPO combustion to diesel combustion, a 6% higher peak pressure was obtained with CPO. Also, CPO started to burn earlier, with a 2.6° shorter injection delay. They observed that CO emission from the combustion of preheated CPO was higher over the whole load range, compared with that of diesel, by an average value of 9.2%. Similarly, an average 29.3% increase in the emission of NOx was observed when fuel was switched from diesel to CPO throughout the range of loading used.

Nazar et al. [43] used preheated crude karanja and neem oil as a fuel in a diesel engine. The tests were conducted with neem oil and karanja oil at different fuel temperatures. They concluded that, with heating, neem oil and karanja oil to the temperature 140°C and 165°C respectively, their viscosity becomes equal to that of diesel. At this condition the brake thermal efficiency of both karanja oil and neem oil are significantly improved and they become closer to diesel. At full load, brake thermal efficiency of neem oil without heating is 24.9% and the same at 140°C is 29.1%; similarly for karanja oil without heating thermal efficiency is 25.36% and at 165°C, it is 29.65%; for diesel it is 31.4%.

Silvio et al. [64] used pure palm oil in stationary diesel engines for the energy supply to small villages in the Amazon basin and studied the performance, emission characteristics and lubricating oil contamination of diesel engine using 100% refined palm oil. Palm oil was heated to 50°C for a first 50 hours of operation and to 100°C for the next 300 hours of operation. It is observed that specific fuel consumption of palm oil is slightly higher than that for diesel at lower loads. Increasing palm oil temperature, the performance and endurance of the diesel generator increases compared to operation in ambient conditions.

Norbert Hemmeriein, et al. [44] conducted a performance test on a divided combustion chamber diesel engine with neat rapeseed oil as fuel. They discussed on energy consumption and engine performance. By order of the Ministry of Research and Technology PORSCHE they investigated six modern diesel engines, where rapeseed oil was used as fuel. They concluded that, engine performance and energy consumption with rapeseed oil is similar to operation with diesel fuel and diesel engines with divided combustion chambers and big cylinder units are able to operate permanently with neat rapeseed oil. It was demonstrated by Masjuki et al. [33] that, by preheating the POME fuel above the conventional temperature, the engine performance, especially the break power output and the exhaust emission characteristics are improved significantly, approaching diesel like performance. The increase in the intake air temperature due to preheating synergistically acts to enhance the reaction rate in the combustion process and hence to give an increase in break power output.

Large numbers of investigations have been carried out using neat vegetable oils as well as their blends with diesel fuel in varying proportions for fuelling different types of diesel engines [24, 38]. Problems like injector choking, excessive carbon deposition on piston, cylinder head and engine exhaust manifold, piston ring sticking, fuel filter clogging, engine oil dilution and polymerization have been reported with use of vegetable oils particularly during long duration operation of engines. Further, it has been reported that vegetable oils blended with diesel up to 20-30 per cent levels could successfully be used for emerging diesel engine in short duration trials.

Samaga et al. [59] in his experiment, showed the test bed performance of a six cylinder automotive diesel engine with blends of 10%, 20%, 30% and 40% honge oil in diesel. It was seen that the best performance was obtained with 10% blend with some improved efficiency as well as reduced NOx and smoke emissions.

Recep Altin et al. [53] evaluated the feasibility of sunflower oil, cottonseed oil soybean oil and their methyl esters for diesel fuel in a DI, four stroke, and single cylinder diesel engine. It was found that vegetable oil fuels gave an acceptable engine performance and exhaust emission levels. Due to their high viscosity, drying with time and thickening in cold conditions, vegetable oil fuels still have some problems, such as flow, atomization and heavy particulate emissions.

Moh’d Abu-Qudais et al. [38] used shale oil as fuel to run a single cylinder and DI diesel engine to compare this fuel in terms of performance, exhaust gaseous emissions and particulate matter. They found shale oil burned more efficiently than the baseline diesel and therefore, resulted in higher engine thermal efficiency. From the experiments it was reported that CO emissions and HC emissions reduced and NOx found to increase with load. Karaosmanoglu et al, [27] determined diesel fuel properties of sunflower oil and long term engine tests of sunflower oil were performed. Engine tests were conducted at a speed of 1600 rpm under part load condition for 50 h with a single cylinder direct injection, air cooled diesel engine, having a bore/stroke ratio of 108:110 min. An overall evaluation of results indicates that the sunflower oil can be proposed as possible substitute for diesel fuel.

Huzayyin et al. [24] conducted experiments by blending jojoba oil with LPG gas. Thus blend of oil and gas was found to be an effective method to reduce engine problems associated with the high viscosity of jojoba oil. It has been reported that brake specific fuel consumption increases and a reduction in engine NOx and soot emission was found using blends of jojoba oil.

Mohamad et al. [37] evaluated waste vegetable oil as a feedstock for biodiesel production. This research was focused on the engine performance and emission characteristics of esterified vegetable oil, when used in a diesel engine. When blends of biodiesel and diesel are used in diesel engines, a significant reduction in hydrocarbon (HC) and particulate matter (PM) is observed but NOx emissions are found to have increased. In general, engine performance and power remains unchanged.

Alberto et al. [2] reviewed the potential of palm oil as an alternative fuel in automotive and industrial diesel engines with respect to its performance and terminological, environmental, economic and social implications. They observed that performance and exhaust gas emissions using palm oil fuel and its blends with conventional diesel fuel in stationary diesel engines are comparable with those of conventional diesel fuel.

Nwafor et al. [45] studied the effect of reducing viscosity by increasing the inlet temperature of vegetable oil fuel in combustion and emission characteristics of diesel engine. As for the results, the unheated oil and diesel fuel operation caused increase in CO production as the load was increased. The concentration of HC in the exhaust was higher than when running on diesel fuel. The overall test results showed that fuel heating was beneficial at low speed and part load operations. Omprakash Herbbal et al. [71] assessed the performance and emission characteristic of blends of Deccan hemp oil with diesel at variable loads and results are compared with diesel. The BTE, BSFC and BSEC are well comparable with diesel and emissions are little higher for 25% and 50% blends.

The conclusions derived from this study were based on initial results and are only intended as a research update. Additional experiments are underway to verify these results and until such time, this information should only be considered preliminary. The experiments conducted in this investigation were systematically controlled to provide reproducible results. Advanced equipment and novel emission measurement protocols provided new scientific information that can be used for important health effect studies of oil combustion generated pollutants. A soybean methyl ester blended into No. 2 fuel oil by 20% by volume showed normal combustion performance comparable to that of No. 2 fuels on a residential oil-fired boiler. No modifications to the procedure or the combustion equipment were required. However, transient CO emissions at cold start increased when the test room and fuel temperature were gradually reduced to levels lower than 15.8°C. The combustion of B-20 bio fuel blend exhibited similar gaseous emissions to those of No. 2 fuel oil, with the exception of SO_2, which was 19.7&2.5% lower. Nitrogen oxide emissions from the bio fuel and No. 2 oil were similar. PM emission concentrations from bio fuel were lower than those from No. 2 oil by 13%. Significant reductions in particle bound sulphate were also noted,(12%), when compared with those from No. 2 oil. These indicate several potential benefits of using the bio fuel blend in residential space and water heating and in industrial processes. Long-term studies need to be conducted to determine appliance performance and unit component integrity over several seasons. Research on the effects of bio fuel matrix on the integrity of certain combustion equipment and the long term chemical and thermal stability of the bio fuel blends needs to be investigated as well. Future research will focus on additional work on cold temperature performance of the blends and necessary modifications to allow for the safe and efficient use of these blends in cold climates. More laboratory experiments are considered necessary to confirm the preliminary data.

Ghassan M et al. [18] studied, “Experimental study on evaluation and optimization of conversion of waste animal fat into biodiesel”. This study was initiated to evaluate and optimize the conversion of waste animal fat (WAF) into ethyl and methyl ester called biodiesel. The physical and chemical characteristics of these esters were much closer to those of diesel fuel than those of fresh vegetable oil or fat, which makes them a good substitute for diesel fuel. An experiment has been performed to determine the optimum conditions for this conversion process using a three factor factorial design for producing biodiesel. The major variables in the transesterification process are determined from the pre-experiments as: reaction temperature, molar ratio of alcohol/oil, alcohol type utilized and catalyst type. Absolute ethanol was found to be better than absolute methanol, since ethanol gives higher conversion and less viscosity at all levels, mainly at 100% excess concentration. Temperature had no detectable effect on the ultimate conversion ratio and viscosity for both ester products. However, higher temperatures decrease the time required to reach maximum conversion, which will be at the expense of the cost of energy. An interaction between time and temperature was found for all conversions. Therefore, $50^{o}C$ was found to be the optimum temperature, and two hours is the optimum time for the conversion of WAFs into biodiesel. WAF is a good raw material for biodiesel production, but 20–25% of this fat is glycerin, which makes it thick and sticky. This glycerin is substituted in a chemical process called transesterification to make the WAF thinner or to reduce its viscosity. From the statistical analysis using three factor factorial, it was found that the main effect for the three factors is excess concentration. Level one is the best (100% excess concentration), as it gives less viscosity and higher mass conversion. At the same time, ethanol is better than methanol, since ethanol gives less viscosity.

Galen J. Suppes et al. [16] studied, “Transesterification of soybean oil with zeolite and metal catalysts” Transesterification of soybean oil with methanol was carried out at 60, 120, and $150^{\circ}C$ in the presence of a series Na_x faujasite zeolite, ETS-10 zeolite, and metal catalysts. The stock zeolites were exchanged with potassium and cesium and Na_x containing alcohol sodium oxide ($NaOx/Na_x$) and occluded sodium oxide ($NaOx/Na_x$). The catalysts were calcined at $500^{\circ}C$ prior to use in order to increase activity. The ETS-10 catalysts provided higher conversions than the Zeolite-X type catalysts. The increased conversions were attributed to the higher basicity of ETS-10 zeolites and larger pore structures that improved intra-particle diffusion. Methyl ester yield increased with an increase in temperature from 60 to $150^{\circ}C$. The metal catalysts increased conversion by one to over two orders of magnitude over the homogeneous reaction with several of the zeolite catalysts performing better than the metal catalysts. The catalyst was reused without observed loss of activity. A preliminary design assessment shows that these catalysts are sufficiently active to be commercially viable contingent upon the costs of the catalysts achieving conversions in excess of 90% at temperatures below 125 ◦C. Several metals and zeolites were identified as effective catalysts for the alcoholysis of soybean oil to methyl esters. The most significant implication of the catalysis of iron, palladium, and nickel is that reactor surfaces containing these metals catalyze alcholysis. This has significance primarily for fundamental work pursuing the understanding of non-catalytic reaction mechanisms. For related fundamental work, the use of metal reactors should be avoided. Nickel was the most catalytic of the metals evaluated and potentially could be configured to promote commercial reactions.

M. Gloria Pereira et al. [30] conducted, “Cleaning oiled shores: laboratory experiments testing the potential use of vegetable oil biodiesels”. In this work, a series of laboratory experiments were carried out to test the potential of vegetable oil biodiesel for the cleaning of oiled shorelines. In batch experiments, biodiesel was shown to have a considerable capacity to dissolve crude oil, which appears to be dependent on the type of biodiesel used. Pure vegetable oil biodiesels (rapeseed and soybean) were significantly more effective in the cleanup of oiled sands (up to 96%) than recycled waste cooking oil biodiesel (70%). In microcosm and mesocosm experiments, oiled sediments were sprayed with biodiesel and subjected to simulated tides. Microcosm experiments revealed that, of those tested, the highest ratio of biodiesel to crude oil, had the highest effectiveness for cleaning fine sands, with ratios of 2:1 (biodiesel: crude oil) giving the best results. In the mesocosm experiments a ratio 1:1 of soybean biodiesel to crude oil removed 80% of the oil in cobbles and fine sands, 50% in coarse sand and 30% in gravel. Most of the oil was removed with the surface water, with only a small amount being flushed through the sediments. Particle size and pore size were important determinants in the cleanup and mobility of crude oil in the sediments in these static systems. It is expected that the biodiesel effectiveness should improve in the natural environment, particularly in exposed beaches with strong wave action. However, more laboratory and field trials are required to confirm the operational use of biodiesel as a shoreline cleaner.

P. Janulis [47] studied, “Reduction of energy consumption in biodiesel fuel life cycle”. In this work, the author has analyzed the life cycle energy balance of rapeseed oil methyl ester. Essential requirements for biofuel are that (a) it should be produced from renewable raw material, and (b) it should have a lower negative environmental impact than that of fossil fuels. Apart from direct assessment of the engine emissions, environmental impact is also determined by performing life cycle analysis. Life cycle energy balance depends on specific climatic conditions and the agro- and processing technologies used. Rapeseed oil methyl ester life cycle energy ratios in Lithuanian conditions have been calculated as a function of rapeseed productivity, oil pressing and transesterification technologies used. Opportunities to improve biodiesel fuel life cycle energy efficiency, by implementing new technologies in agriculture as well as in industrial processing, were reviewed. The effectiveness of new technologies was evaluated on the basis of energy balance comparison. Understanding the importance of the environment and possible production- and consumption-related negative environmental impacts has forced science to look for ways to evaluate this impact. For this purpose, life cycle assessment methodology has been created and presented in the standards of the International Standard Organization ISO 14040–14049. Life cycle analysis is used to evaluate environmental impact and potential factors related to product life cycle energy balance, including raw materials, production, consumption, and waste utilization. Fuel life cycle analysis starts with raw material extraction stage and ends with fuel consumption in vehicle engine. Life cycle analysis demonstrates the additional quantity of energy required to turn the energy present in the raw materials into useable energy of the fuel. Direct (petroleum products, electricity) and indirect (used for production of materials and equipment) energy consumption is evaluated in fuel life cycle. Biodiesel fuel life cycle analysis calculates the following indicators: R1-the ratio of biodiesel fuel energy (calorific value) to the total energy used for fuel production, R2-the ratio of energy accumulated in all products (including by-products) obtained in the bio fuel production process to the total energy consumed for the fuel production, and eco balance R3-the ratio of fuel energy (calorific value) to the total energy related solely to the bio fuel production.

Zhang M.A et al. [68] studied, “Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis”. Exploring new energy resources, such as biodiesel fuel, is of growing importance in recent years. Biodiesel, derived from vegetable oil or animal fats, is recommended for use as a substitute for petroleum-based diesel mainly because biodiesel is a renewable, domestic resource with an environmentally friendly emission profile and is readily biodegradable. The use of biodiesel as a fuel has been widely investigated. Its commercial use as a diesel substitute began in Europe in the late 1980s. At present, the most common way to produce biodiesel is to transesterify triacylglycerols in vegetable oil or animal fats with an alcohol in the presence of an alkali or acid catalyst. Methanol is the commonly used alcohol in this process, due in part to its low cost. The products, fatty acid methyl esters (FAME), are called biodiesel and include glycerin as a byproduct. Alkali catalyzed transesterification has been most frequently used industrially, mainly due to its fast reaction rate. Sodium hydroxide or potassium hydroxide is the usual alkali catalyst. In contrast, acid-catalyzed transesterification has received less attention because it has a relatively slow reaction rate. Nevertheless, it is insensitive to free fatty acids in feedstock oil compared to the alkalicatalyzed system. The typical acid catalyst used in the reaction is sulfuric acid. Compared to petroleum-based diesel, the high cost of biodiesel is a major barrier to its commercialization. It costs approximately one and a half times that of petroleum-based diesel depending on feedstock oils (Prokop, 2002; Lott, 2002). It is reported that approximately 70–95% of the total biodiesel production cost arises from the cost of raw material; that is, vegetable oil or animal fats (Krawczyk, 1996; Connemann and Fischer, 1998). Therefore, the use of waste cooking oil should greatly reduce the cost of biodiesel because waste oil is available at a relatively low price. In a previous study, four different process flow sheets for producing biodiesel from virgin vegetable oil or waste cooking oil by alkali- or acid-catalyzed transesterification were developed (Zhang et al. 2003). A comparison of these processes was presented from the point of view of their process technology. The result showed that the acid-catalyzed process from waste cooking oil was potentially a competitive alternative to the commonly used alkali-catalyzed process. Besides the technological evaluation, economic feasibility is also of great importance in assessing process viability. Thus, the main objective of the present article is to assess these processes on an economic basis. In this way, a better evaluation of the biodiesel production process will be achieved from both the technological and economic points of view. In addition, a sensitivity analysis of each process is presented to identify the major factors affecting the economic viability of biodiesel production 2.

A. Durana et al. [3] studied, “An easy correlation to determine soluble and insoluble fractions in diesel particulate matter”. Numerous mechanisms of diesel particulate matter formation have been postulated in literature on the basis of theoretical considerations which include nucleation and growth in the cylinder, condensation as well as gas adsorption and absorption, mainly in the dilution process. However, few authors have tried to experience individual mechanisms in the laboratory. For example, Popovitcheva et al. have recently characterized aircraft combustor soot, and determined in the laboratory its low adsorption capacity of some non-polar gases, such as benzene. As a result of this deficiency of experiments, probably due to the difficulty in obtaining enough soot particles for characterization and investigation purposes, the extent in which each of the above mechanisms participates in the global process of DPM formation is still unresolved. Furthermore, most of the current models are based on theoretical equilibrium conditions, which have never been demonstrated in the laboratory. On the other hand, the scrubbing effect of sulphuric acid has already been reported, and the effect of sulphuric acid on the formation mechanism and properties of particulates emitted to the atmosphere has been simulated, but no mathematical correlation with global DPM formation has been formulated. In this work, experimental fitting of emission data from five fuels and three mixtures will allow to propose an easy equation to calculate both the insoluble and soluble fractions in DPM into the experimental range. As a consequence, the relative importance of each mechanism involved in the DPM formation process will also be quantified. This knowledge will be useful to propose schemes to reduce particulate emissions to the atmosphere.

M.P. Dorado et al. [34] studied, “Exhaust emissions from a diesel engine fueled with transesterified waste olive oil”. The exhaust emissions of a diesel direct injection Perkins engine fueled with waste olive oil methyl ester were studied at several steady state operating conditions. Emissions were characterized with neat biodiesel from used olive oil and conventional diesel fuel. Results revealed that the use of biodiesel resulted in lower emissions of CO (up to 58.9%), CO_2 (up to 8.6%, excepting a case which presented a 7.4% increase), NO (up to 37.5%) and SO_2 (up to 57.7%), with increase in emissions of NO_2 (up to 81%, excepting a case which presented a slight reduction). Biodiesel also presented a slight increase in brake-specific fuel consumption (lower than 8.5%) that may be tolerated due to the exhaust emission benefits. Combustion efficiency remained constant using either biodiesel or Diesel fuel. The proposed alternative for diesel fuel could significantly decrease the enormous amount of waste frying oil, furthermore becoming less dependent on fossil oil imports and decreasing environmental pollution. In this work, the fuel tests were performed with a 2500 cm^3, three cylinder, four-stroke, water-cooled, 18.5:1 compression ratio, direct injection diesel engine Perkins AD 3-152.The maximum torque was 162.8 Nm at 1300 rpm, and the maximum engine power was 34 kW at 2250 rpm (DIN 6270-A). The engine was not new but reconditioned to original specifications. Emission tests were carried out with a portable pollution emissions monitor, model 9950, from Teledyne Brown Engineering, USA. It consists of a stainless steel probe which is connected to a monitor by a flexible hose. Once the auto zero is completed, the probe can be inserted into the sample stream. The model incorporates advanced microprocessor technology which provides a menu-driven interface with all functions through front panel controls and a large LCD display. The model provides an emission analysis with an accuracy of better than 3% of full scale. It measures SO_2, O_2, CO, NOx (NO & NO_2) and calculates the concentration of CO_2.

M.A. Kalam [33] studied, "Biodiesel from palm oil-an analysis of its properties and Potential". This paper presents the experimental results carried out to evaluate the effect of anticorrosion additive in biodiesel (from palm oil) on diesel engines, performance, emissions and wear characteristics. This biodiesel is defned as the methyl ester of palm oil also known as palm oil diesel (POD). The results of this investigation will be used to find compatible lubricant for biodiesel engine. The production cost of biodiesel is dependent on the regional prices of bio fuel, labor, land and processing plant cost, etc. The physico-chemical properties of POD meet the requirement of diesel engine combustion and are comparable with other biodiesels such as soybean and rapeseed oils. Fuel B (50 ppm anticorrosion/corrosion inhibitor +15% POD + 85% OD) increased brake power and reduced exhaust emissions compared to base fuel OD. It decreases wear metals (Fe, Cu, Al and Pb) and additives (Zn, Ca) depletion as compared to OD. Viscosity changes are normal form both the POD blends. The TBN decreases with increasing POD in blends. Hence, an anticorrosion additive was efective with POD blends.

G. Antolin et al. [15] studied, "Optimization of biodiesel production by sunflower oil transesterification". In this work the transformation process of sunflower oil in order to obtain biodiesel by means of transesterification was studied.Taguchi's methodology was chosen for the optimization of the most important variables (temperature conditions, reactants proportion and methods of purification), with the purpose of obtaining a high quality biodiesel that fulfils the European pre-legislation with the maximum process yield. Taguchi's Design of Experiments (Taguchi, 1989) was carried out on 20 tests in order to determine the operation conditions that maximized yield and fulfilled the specifications enforced by the European prelegislation on biodiesel quality related to mono, di, and triglycerides, methanol, free glycerol and fatty acid contents. The following variables were studied:- Catalyst amount:- Experiments were carried out with 0.28% and 0.55% w/w of potassium hydroxide related to the quantity of oil that had to be transesterified. Methanol amount:-Methanol in excess is necessary, therefore two and three times the stoichiometric quantity was used. Reaction temperature:- The chosen levels were 60 and 70^{o}C. Washing - Two alternatives were used:- absence of washing or with two washings, the first of the two with a 5% w/w solution of phosphoric acid and the second with pure water. Finally, sunflower methyl esters were characterized to test their properties as fuels in diesel engines, such as viscosity, flash point, cold filter plugging point and acid value. Results showed that biodiesel obtained under the optimum conditions is an excellent substitute for fossil fuels.

J.W. Goodrum [25] studied, "Volatility and boiling points of biodiesel from vegetable oils and tallow". Standards and quality control in the manufacture and distribution of biodiesel are being developed to assure that reliable and consistent fuels are supplied to users. Vapor pressure, Pv, and boiling point (bp) data hold promise as key fuel properties for biodiesel since they have played a vital role in quality control in the petroleum based diesel fuel (D2) industry. D2 is defined by a specific bp range; its manufacture is based on control of the fuel's bp range. Further, D2 is winterized or regionally adjusted by changing its boiling range slightly. If a practical method for fast, routine measurement of bp and temperature dependence of vapor pressure were available, a specified bp would be a key test for quality of a biodiesel fuel. For example, multiple bps for a single solution indicates the presence of chemically distinct components. Therefore, two bps would indicate the presence of approximately 20% or more of impurities, such as un-reacted vegetable oil, glycerol, etc. The vapor pressures and boiling points of selected methyl esters and vegetable oils are proposed as quality control metrics for biodiesel. This type of data was obtained by a rapid new method using thermo gravimetric analysis (TGA).One atmosphere boiling points (bps) and temperature-dependent vapor pressures from 1 atm down to 5.332 kPa (40 mm Hg)were measured for methyl and ethyl esters of rapeseed oil, canola oil, soybean oil, and tallow. Boiling points (1 atm) ranged from 340˚C to 375˚C. Methyl and ethyl esters of a given oil differ by ca. 5˚C in bps. These results are discussed in terms of the fatty acid composition of the esters and oils.

D. Kusdiana et al. [12] studied, “Kinetics of transesterification in rapeseed oil to biodiesel fuel as treated in supercritical methanol”. The supercritical experiments of methanol with rapeseed oil were carried out with a batch-type of reaction vessel. Therefore, the temperature and the pressure inside the reaction vessel are different in different reaction conditions. A highly efficient transesterification process has been described and the proposed kinetics in transesterification of rapeseed oil has been proven to fit very well with those of experimental data. A reaction temperature of 350.8^{o}C with the molar ratio of methanol being 42 was considered as the best condition for a free-catalyst process of biodiesel fuel production. The supercritical methanol method, therefore, offers a potentially low cost method with simpler technology for producing an alternative fuel for compression ignition engines. The considerable yield of methyl esters by the environmentally friendly method renders this technique ideally suited for industrialization.

O.E. Ikwuagwu et al. [46] studied, “Production of biodiesel using rubber seed oil” Rubber seed oil was extracted, and its physical and chemical characteristics determined. The crude oil was bleached and the ester-fuel (methyl-ester) was prepared by trans-esterification with 6-molar excess of methanol using sodium hydroxide as a catalyst. Methyl ester yield and fuel properties of the oil (crude and bleached) and its methyl ester were determined and compared to that of commercial diesel fuel. The analysis of the properties in comparison to commercial diesel fuel showed that trans-methylation improved the fuel properties of the oil. The viscosity was substantially reduced from 37.85 to 6.29 Cst. Calculated cetane index (increased from 34.00 to 44.81), other fuel properties were also found to improve. The results support the choice of monosters, in place of straight rubber seed oil, as having better potential for use as alternative diesel fuel. However, oxidative stability was reduced by *trans*-methylation. The proximate composition of rubber seed kernel indicates that the seed contains 45.63% oil, 60.71% ash, 3.71% moisture, 22.17% protein, and 24.21% carbohydrate. The result shows that rubber seed is a potential source of oil and hence justifies the study on possible industrial uses. The result shows that *trans*-methylation improved the following fuel properties of the oil: specific gravity; viscosity; flash point; fire point; ash content; cetane index; and petroxide value. The comparison of these properties with that of diesel fuel shows that the methyl ester has relatively closer fuel properties to diesel fuel than that of oil. The calculated cetane index as well as other fuel properties was found to be improved. From the results, crude rubber seed oil has the highest AOM induction period of 13.7 h, followed by 12.6 h for refined oil and 8.7 h for the methyl ester. The refining of the oil was observed to reduce the AOM induction time of the oil and is consistent with the report of Quick (1989), that ‘refining reduces storage life of oils’, having an AOM induction time of 8.7 h. The observed decrease in oxidative stability of the refined oil and methyl ester is as a result of the fact that the refined oil and methyl ester are significantly less viscous than the parent rubber. The methyl ester showed least oxidative stability, seed oil. This lower viscosity allows a higher oxygen diffusion rate which increases contact between oxygen and the refined oil and ester molecules, respectively.

M. Sasidharan et al. [31] studied, “Transesterification over various zeolites under liquid-phase conditions”. Keto esters are widely used as synthons in several natural product synthesis and industrial applications. For example, terpene esters, commonly used as flavor and fragrance compounds for a variety of foods and beverages, are synthesized using various homogeneous chemical reagents via transesterification. However, since the transesterification is an equilibrium process, it is accelerated by the simultaneous removal of low-boiling coproduct alcohol during the process by a zeotropic distillation. The transesterification reaction has been effected with various homogeneous catalysts such as distannoxanes, $InCl_3$, $LiClO_4$, titarnum(IV) alkoxide, and sulphated SnO_2, A few heterogeneous catalysts like envirocat EPZG , amberlyst-15 , and polymer supported lipase have also been employed recently. Although many methods are available for this reaction, the transesterification of allylic alcohols is rather difficult as it leads to successive decarboxylation and rearrangement. Moreover, the reaction failed with aromatic substrates over sulphated SnO_2 catalyst. Distannoxanes are reported to give good yields of keto esters but the catalysts are difficult to prepare. Furthermore, due to environmental demands, there has been considerable interest in developing new inorganic solid-acid catalysts such as zeolites to replace the homogeneous catalysts. The availability of a range of zeolites with different pore-size and tunable acidity coupled with high thermal stabilities in the protonic form had considerable impact over their utility in the field of various fine chemicals synthesis. Zeolite was found to be a suitable catalyst for the transesterification reaction to prepare a variety of building blocks for the synthesis of natural products like podophyllotoxin.

Piyali Das et al. [48] studied, “Bio oil from pyrolysis of cashew nut shell-characterization and related properties.” In India Cashew nut cultivation now covers a total area of 0.70 million hectares of land, producing over 0.40 million metric tons of raw Cashew nuts. The cashew (Anacardium Occidentale) is a tree in the flowering plant family Anacardiaceae. The plant is native to northeastern Brazil, where it is called by its Portuguese name Caju (the fruit) or Cajueiro (the tree). It is now widely grown in tropical climates for its cashew "nuts" and cashew apples. According to the invention CNSL is subjected to fractional distillation at 200° to 240°C under reduced pressure not exceeding 5mm. mercury in the shortest possible time which gives a distillate containing cardol and the residual tarry matter. For example, in the case of a small quantity of oil, say 200 ml/ the distillation period is about 10 to 15 minutes. A semi-commercial or commercial scale distillation of CNSL may however take longer times. It has been found that there are certain difficulties of operation with regard to single-stage fractional distillation method, i.e. frothing of the oil which renders difficult the fractionation of cardol and also formation of polymerised resin. These difficulties can be overcome in the two-stage distillation, if care is taken not to prolong the heating; this is to avoid the undue formation of polymerised resins and possible destruction partially or completely of the cardol or anacardol.

Watts K.C. et al. [72] conducted experiment for predicting the viscosity of biodiesel fuels from their fatty acid ester Composition. This investigation presents a method, which has been verified experimentally, for predicting the viscosities of biodiesel fuels from the knowledge of their fatty acid composition. The applicability of a logarithmic mixture equation was verified using controlled mixtures of standard fatty acid esters and natural biodiesels. Several binary, ternary and quaternary mixtures of fatty acid ethyl ester (FAEE) gas chromatography (GC) standards were formulated. The viscosities of fifteen biodiesel types were predicted based on their fatty acid composition. This is most likely a principal contributing factor to the variation in performance of some biodiesel fuel types. The viscosity of biodiesel fuels reduce considerably with increase in unsaturation. Contamination with small amounts of glycerides significantly affects the viscosity of biodiesel fuels.

From the above literature survey, it is observed that no much work has been carried out by using esters of cashew nut (Cardanol) oil as an alternative fuel in diesel engines. Thus for the environmental reasons and to consider the future energy requirements, now the time has come to give more emphasis on investigation of applications of esters of cashew nut oil (Cardanol) in various industrial & transport sectors. In the present investigation esters of Cardanol and their blends i.e. B10, B15, B20 and B25, with diesel oil at various test parameters are to be evaluated.

2.4 DIESEL FUEL [69]

The middle distillate fuels are among the cheapest end products of the refinery process since they require little further treatment after leaving the distillation plant. Diesel oil comes after gasoline and kerosene during the distillation of petroleum crude.

2.4.1 Diesel Fuel Classification [69]

The ASTM Designation D 975-60T classifies diesel fuels into 3 grades, namely

1. **No. 1-D.** This is a volatile distillate fuel oil used for engines in service requiring frequent speed and load changes. This is usually a straight-run fuel.
2. **No. 2-D.** This is a distillate fuel oil of lower volatility than No. 1-D, and used for engines in industrial and heavy service. This fuel may contain straight-run and/or cracked components.

3. **No. 4-D.** This is a fuel oil for low and medium speed engines. This fuel may either straight-run or cracked with some residuals.

The British Standards Institution (BSI) has two specifications for diesel fuel, namely,

1. BS 2869:1970, “Petroleum Fuels for Oil Engines and Burners for Non-marine Use,”
2. BS MA 100, “Petroleum Fuels for Marine Oil Engines and Boilers.”

The standard specifies engine fuels A1, A2, B1, B2, C1, and C2 out of which

a) A1 and A2 are gas oils
b) B1 and B2 are diesel fuels
c) C1 and C2 are kerosenes.

The National Annual Diesel Fuel Survey classifies diesel fuels into four types, depending upon the service for which the manufacturers recommend these fuels. These are the following:

Type C-B	Diesel fuel oil for city bus and similar operation.
Type T-T	Fuel for diesel engines in trucks, tractors, and similar services.
Type R-R	Fuel for Railway diesel engines.
Type S-M	Heavy distillates and residual fuels for large stationary and marine engines.

In India, two categories are generally found to exist, namely

HSD	High speed diesel used for high speed diesel engines like trucks, buses, tractors, and railway engines.
LDO	Light diesel oil used for slow speed engines like stationary engines, marine engines and diesel power plants.

It is found that specific gravity, flash point, viscosity, sulfur content, and carbon residue increase with increase in service severity. The cetane number (which measures the fuel’s ignition quality) decreases with increase in service severity. There is a decrease in volatility with increase in service severity. Properties are, however, inter-related and it is difficult to isolate the effect of any single variable.

It is found that the self-ignition temperature of the normal paraffins decreases as the length of the chain increases. Since the cetane rating of the fuel is a measure of the ignition characteristics of the fuel, it can be concluded that the heavier members of the paraffin family have higher cetane ratings. In fact, cetane, $C_{16}H_{34}$ (hexadecane) is the primary reference fuel in the cetane scale with an arbitrary cetane rating of 100 while other normal paraffins have cetane ratings that vary almost linearly with the length of the chain. The order of excellence of cetane ratings is related to the properties as well as the chemical structure of the fuels. From the table below (Table2.1) it can be seen that normal paraffins have the lowest specific gravity and the highest cetane number.

Table 2.1 Characteristics of Hydrocarbons as Diesel Fuels

Hydrocarbon	**General Formula**	**Characteristics**
1.N-paraffin	C_nH_{2n+2} (Straight chain)	Low specific gravity and high cetane number
2. Iso-paraffin	C_nH_{2n+2} (Branched Chain)	Same specific gravity as S. No. 1 and lower cetane no. and boiling point
3. Cyclo-paraffins (naphthenes and olefins)	C_nH_{2n} boiling point than S. No. 1	Higher specific gravity and boiling point than S.No.1 but lower cetane no than S.No.1-3
4. Aromatics (benzene rings)	C_nH_{2n-6} (for exampleC_6H_6)	Higher specific gravity and Boiling point but lower cetane no
5. Naphthalenes (Condensed benzene or naphthalene rings)	C_nH_{2n-12} (for example $C_{10}H_8$)	Highest specific gravity and and boiling point and lowest cetane number

2.5 BIODIESEL

Definition:

Biodiesel’s definition has been a work in progress. Since the early 1900s, bio diesel has been defined as an alternative form of diesel fuel made from vegetable oils or animal fats and alcohol [10]. The definition of biodiesel was neither legally definable nor defensible in the United States for about a century. This changed when biodiesel was registered with the U.S. Environmental Protection Agency (EPA) as a fuel and a fuel additive under section 211(b) of the Clean Air Act. With help from the American Society of Testing & Materials (ASTM), subsequent legislation such as the Energy Policy Act (EPAct) helped further define biodiesel. In December 2001, the ASTM issued and defined physical/chemical constraints for biodiesel and subsequently for mixtures of biodiesel with diesel fuel. An important distinction needs to be made between biodiesel and biodiesel blends. Biodiesel is commonly mixed with diesel No. 2 to form a biodiesel blend. As stated above, a mixture of biodiesel and diesel is not biodiesel, but is referred to as a biodiesel blend. Pure biodiesel, also known as neat biodiesel, is commonly noted as B100, indicating that the fuel has 100 percent biodiesel (noted by the 100) and 0 percent diesel. The most common biodiesel blend is B20, which contains 20 percent biodiesel and 80 percent diesel.

2.5.1 Bio diesel Manufacture [10]

Biodiesel is derived from biological sources, such as vegetable oils or fats, and alcohol. Commonly used feed stocks are shown in Table 2.2.

Table 2.2: Feed stocks Used for Biodiesel Manufacture

Vegetable Oils	**Animal Fats**	**Other Sources**
✍ Soybeans ✍ Rapeseed ✍ Canola Oil ✍ Safflower Oil ✍ Sunflower Seeds ✍ Yellow Mustard Seed	✍ Lard ✍ Tallow ✍ Poultry Fat	✍ Recycled Restaurant Cooking Oil (a.k.a.Yellow Grease)

2.5.2 Bio diesel production [10]

Many standardized procedures are available for the production of biodiesel fuel. The commonly used methods for bio-fuel production are elaborated below:

2.5.2.1Blending

Vegetable oil can be directly mixed with diesel fuel and may be used for running an engine. The blending of vegetable oil with diesel fuel was experimented successfully by various researchers. A diesel fleet was powered with a blend of 95% filtered used cooking oil and 5% diesel in 1982. In 1980, Caterpillar Brazil Company used pre-combustion chamber engines with a mixture of 10% vegetable oil to maintain total power without any modification to the engine. A blend of 20% oil and 80% diesel was found to be successful. It has been proved that the use of 100% vegetable oil was also possible with some minor modifications in the fuel system. The high fuel caused the major problems associated with the use of pure vegetable oils as fuel, such as viscosity in compression ignition engines. Micro-emulsification, pyrolysis and transesterification are the remedies used to solve the problems encountered due to high fuel viscosity.

2.5.2.2 Micro-Emulsification

To solve the problem of high viscosity of vegetable oil, micro emulsions with solvents such as methanol, ethanol and butanol were used. A micro emulsion is defined as the colloidal equilibrium dispersion of optically isotropic fluid microstructures with dimensions generally in the range of 1–150 nanometer formed spontaneously from two normally immiscible liquids and one or more ionic or non-ionic amphiphiles. These can improve spray characteristics by explosive vaporization of the low boiling constituents in the micelles. All micro emulsions with butanol, hexanol and octanol will meet the maximum viscosity limitation for diesel engines.

2.5.2.3Thermal Cracking

Cracking is the process of conversion of one substance into another by means of heat or with the aid of a catalyst. It involves heating in the absence of air or oxygen and cleavage of chemical bonds to yield small molecules. The pyrolyzed material can be vegetable oils, animal fats, natural fatty acids and methyl esters of fatty acids. The pyrolysis of fats has been investigated for more than 100 years, especially in those areas of the world that lack deposits of petroleum. Since World War-I, many investigators have studied the pyrolysis of vegetable oils to obtain products suitable for engine fuel application. Tung oil was saponified with lime and then thermally cracked to yield crude oil, which was refined to produce diesel fuel and small amounts of gasoline and kerosene.

2.5.2.4 Transesterification

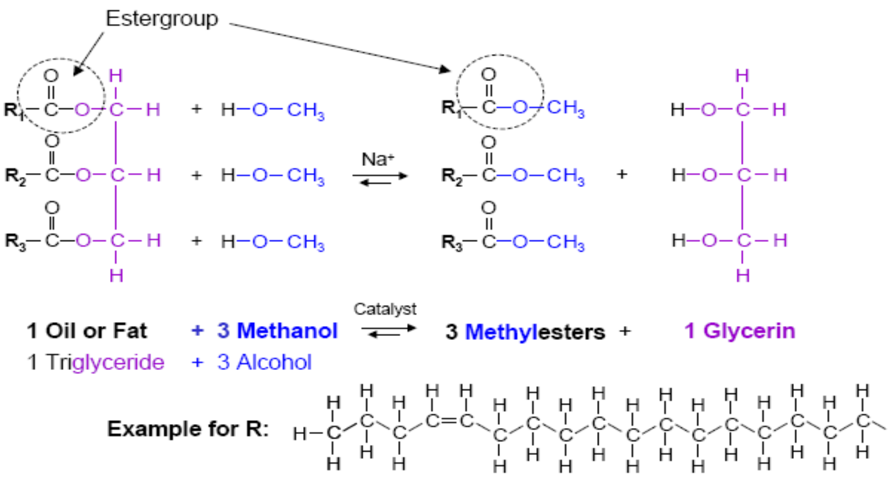
Transesterification is otherwise known as alcoholysis. It is the reaction of fat or oil with an alcohol to form esters and glycerin. A catalyst is used to improve the reaction rate and yield [48].Among the alcohols, methanol and ethanol are used commercially because of their low cost and their physical and chemical advantages. They quickly react with tri-glycerides and NaOH and are easily dissolved in them. To complete a transesterification process, 3:1 molar ratio of alcohol is needed. Enzymes, alkalis, or acids like lipases, sodium hydroxide and sulphuric acid,can catelize the reaction respectively. Among these, alkali transesterification is faster and hence it is used commercially. A mixture of vegetable oil and sodium hydroxide (used as catalyst) are heated and maintained at 65 ºC for 1 hour, while the solution is continuously stirred. Two distinct layers are formed; the lower layer is glycerin and the upper layer is ester. The upper layer (ester) is separated and moisture is removed from the ester by using calcium chloride. It is observed that 90% ester can be obtained from vegetable oils.

2.5.2.5 Transesterification of vegetable oil [3, 34]

In transesterification, which is a popular conditioning of vegetable oil in current practice, one ester is converted into another. The reaction is catalyzed by either acid or base involving reaction with an alcohol, typically methanol, if a bio-fuel is the desired product. This section deals with steps involved in the preparation of biodiesel from untreated vegetable oils. A stoichiometric material balance yields the following simplified equation.

$$\begin{array}{llcll} \text{Fat or oil} & +\ \ 3\ \text{Methanol} & \longrightarrow & 3\ \text{Methyl esters} & +\ \ \text{Glycerol} \\ 1000\ \text{Kg} & +\ 107.5\ \text{Kg} & & 1004.5\ \text{Kg} & +\ 103\ \text{Kg} \end{array}$$

The chemical reaction involved in this process is shown below.



The reaction proceeds above room temperature (60-75º C) with a conversion efficiency of 80-90%, in an excess of methanol within 1-2 hours. The remaining 10-20% is glycerol, mono/di/triglycerides and free fatty acids. Much of free fatty acids are converted into sodium salt of the fatty acid (soap) and water.

Selection of Raw Materials

- ***Moisture free oil sample***: Every time 2 liters of oil is taken in the reactor. To make it moisture free, the oil sample is heated to about 110ºC for one hour. Raising the oil temperature and cooling it back to room temperature does not altered, change the properties of oil.
- ***Anhydrous methyl alcohol****:* 99% grade laboratory reagent type methyl alcohol, ethanol and iso-amyl alcohol are chosen.
- ***Catalyst:*** Sodium hydroxide is selected for the purpose of catalyzing the reaction.

2.5.2.6 Transesterification Procedure

Widely used and accepted process to reduce the viscosity of triglycerides is transesterification. In the transesterification of vegetable oils, triglycerides react with alcohol in the presence of a strong acid or base, producing a mixture of fatty acid, alkyl esters and glycerol. The chemical reaction involved in this process is shown in Figure 2.1. The experimental set up for the transesterification process is shown in Figure 2.2.

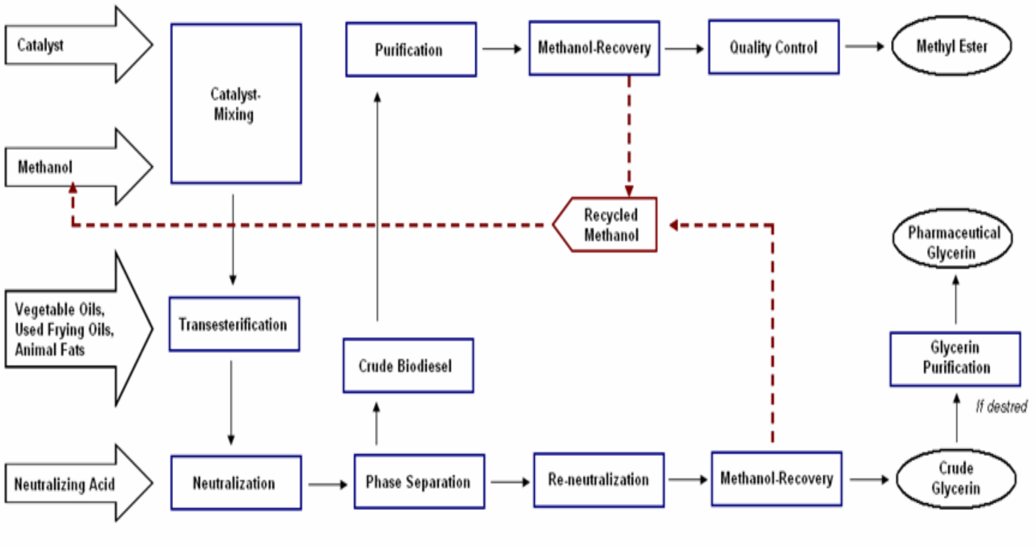
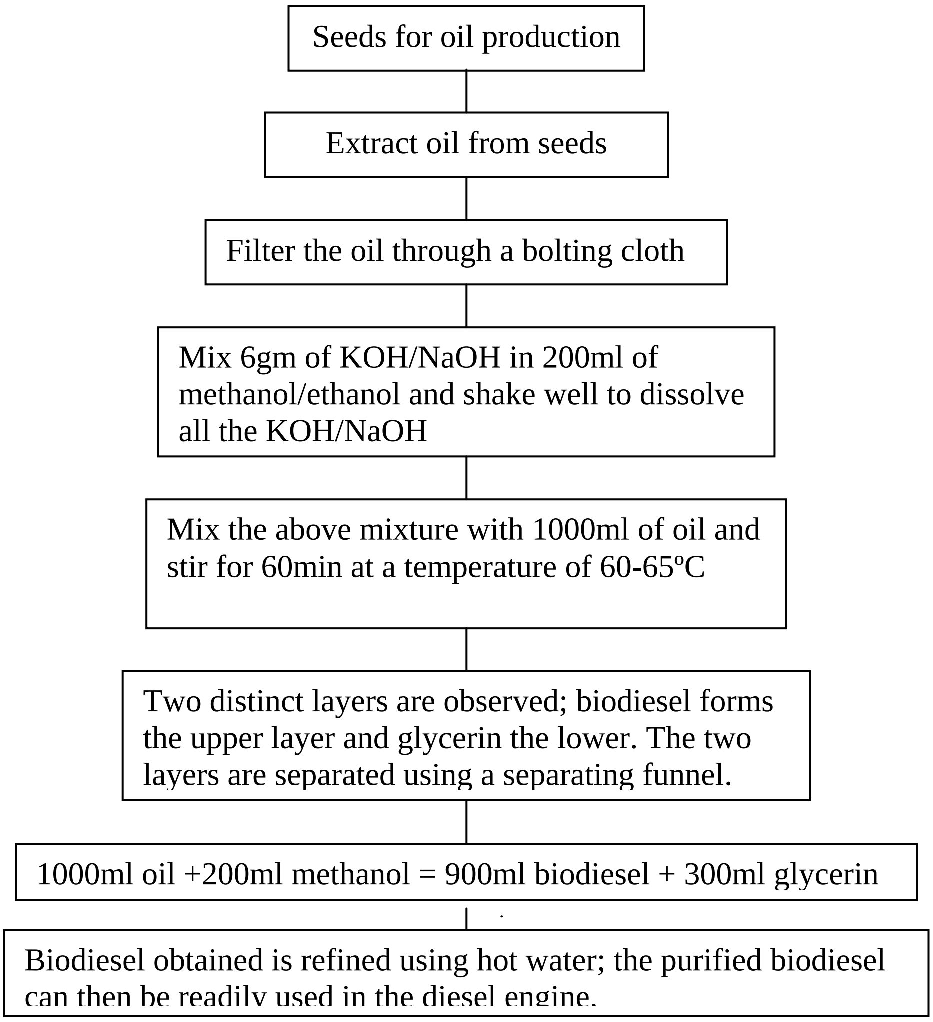


Figure2.1: Basic Scheme for Biodiesel production

Figure 2.2 Setup used for the Transesterification process

2.5.2.7 Transesterification Process details

Flow chart for Transesterification process is shown in Figure 3.4



Filtering

Oil is filtered to remove solid particles. The oil is required to be warmed up a bit first to get it to run freely; 35°C should be enough. Cartridge filter is used for the same.

Removing the water

The oil is heated to remove water content, otherwise this can slow down the reaction and cause saponification (soap formation). Less the water in the oil the better. The temperature is raised to 100°C and maintained at this temperature to allow any water particles to boil off and then allowed to cool to 35^0C.

Preparation of sodium methoxide

About 6 grams of catalyst NaOH pellets are dissolved in 200 ml of methanol to prepare methoxide solution, which is required to activate the alcohol. Then stirring is done vigorously in a covered container until the sodium hydroxide (NaOH) is dissolved completely. The mixture is protected from atmospheric carbon dioxide and moisture, as both destroy the catalyst.

Caution

Treat sodium methoxide with extreme caution! Do not inhale any vapours!. If the sodium methoxide gets splashed on the skin, it would burn without causing any feeling (killing the nerves). Wash immediately with lots of water.

Heating and mixing

Oil is preheated to 50-60^{0}C (<65^{0}C). Sodium methoxide solution is added to oil and stirring continuously for 50 minutes to the one hour maintaining the same temperature. The reaction is often completed in 30 minutes, but the longer duration better for conversion. This separates the methyl esters form the glycerin.

Settling and separation

The mixture is allowed to settle and cool for at least 8 hours, preferably longer, in a separating funnel. The mixture is allowed to settle by gravity in a separating funnel overnight. It is observed that there are two distinct layers formed. The semi-liquid glycerin at the bottom has a dark brown colour and bio-diesel is honey coloured and is at the top. Without disturbing the funnel, the bottom layer is separated out, which is glycerin. The layer, which is retained in the funnel, is methyl ester of vegetable oil.

Washing and drying

Water washing is done to remove any moisture and emulsion. To do this, water of about 30% by volume of the ester is added and the mixture is heated to 120^{o}C for 1 hour to make the ester free from moisture. After heating, the mixture is once again transferred to the separating funnel wherein the water with any emulsion formed settles at the bottom. The upper layer is pure methyl ester i.e., bio-diesel, ready for the use in diesel engine.

2.5.3 Biodiesel Fuel Properties [10]

Table2.3: ASTM Specifications (D6751) for B100 [10]

Property	**ASTM**	**Units**
Flash Point	D93	130 min. °C
Water & Sediment	D2709 0.050 max.	% Volume
Kinematic Viscosity (40 °C)	D445 1.9-6.0	mm^2/sec
Sulfated Ash	D874 0.020 max.	% mass
Sulfur	D5453 0.05 max.	% mass
Copper Strip Corrosion	D130 No.3 max.	
Cetane	D613 47 min.	
Cloud Point	D2500 Report	°C
Carbon Residue (100% Sample)	D4530* 0.050 max.	% mass
Acid Number	D664 0.80 max.	Mg KOH/gm
Free Glycerin	D6584 0.020 max.	% mass
Total Glycerin	D6584 0.240 max.	% mass
Phosphorous Content	D4951 0.001 max.	% mass
Distillation Temperature,		
Atmospheric Equivalent		
Temperature (90% Recovered)	D1160 360 max.	°C

Biodiesel is made up of fourteen different types of fatty acids, which are transformed into fatty acid methyl esters (FAME) by transesterification. Different fractions of each type of FAME present in various feed stocks influence some properties of fuels. Table 2.4 shows some of the properties defined in the ASTM standards for diesel and biodiesel.

According to the study, cloud and pour points were slightly lower for ethyl esters than methyl esters. However, ethyl esters showed slightly higher viscosity and slightly less power and torque.

Table 2.4: Comparison of Fuel Properties between Diesel and Biodiesel [10]

SL.No	Fuel Property	Diesel	Biodiesel
1	Fuel Standard	ASTM D975	ASTM PS 121
2	Fuel composition	C10-C21 HC	C12-C22 FAME
3	Lower Heating Value, Btu/gal	131,295	117,093
4	Kin. Viscosity, @ 40° C	1.3-4.1	1.9-6.0
5	Specific Gravity kg/l @ 60° F	0.85	0.88
6	Density, lb/gal @ 15° C	7.079	7.328
7	Water, ppm by wt	161	.05% max
8	Carbon, wt %	87	77
9	Hydrogen, wt %	13	12
10	Oxygen, by dif. wt %	0	11
11	Sulfur, wt %	.05 max	0.0 - 0.0024
12	Boiling Point (°C)	188-343	182-338
13	Flash Point (°C)	60-80	100-170
14	Cloud Point (°C)	-15 to 5	-3 to 12
15	Pour Point (°C)	-35 to -15	-15 to 10
16	Cetane Number	40-55	48-65
17	Stoichiometric Air/Fuel Ratio wt./wt.	15	13.8
18	BOCLE Scuff, grams	3,600	>7,000
19	HFRR, microns	685	314

2.5.4 Highlights of Fuel Properties

- The *lower heating value* refers to the energy content, or energy per unit mass, of the fuel excluding the heat produced by evaporation of water vapor in the fuel.
- This results from the higher oxygen content of the fuel that produces more complete combustion of the fuel and soot.
- By weight, biodiesel contains less carbon, sulfur and water and more oxygen than diesel. The reduced carbon content decreases tailpipe emissions of carbon monoxide (CO), carbon dioxide (CO_2) and soot (elemental carbon). The lower

sulfur content of biodiesel is important for two primary reasons. First, as a low sulfur fuel, biodiesel produces little or no emissions of sulfur dioxide (SO_2).

- SO_2 contributes to respiratory illness, aggravates existing heart and lung diseases, contributes to the formation of acid rain, can impair visibility, and can be transported over long distances.
- Biodiesel’s higher oxygen content allows it to burn more completely than conventional diesel, thereby reducing hydrocarbon and carbon monoxide emissions. Biodiesel and diesel have a common *boiling point*, but biodiesel has a higher *flash point* – the temperature at which a fuel will catch fire – because biodiesel has a high number of FAMEs which are generally not volatile. Thus, biodiesel is safer to handle at higher temperatures than diesel. Biodiesel is similar to diesel no. 2 in that both fuels need to be used cautiously in cold climates, as wax crystals can form in either fuel at lower temperatures. These wax crystals can plug fuel filters, causing engine stumbling or stalling. A variety of temperatures are used to reflect wax crystal formation, two of which – cloud point and pour point – are listed in Table 2.4.
- *Cloud point* is the temperature at which a haze or cloud of wax crystals first appears in the fuel when it is cooled under test conditions.
- *Pour point* is the lowest temperature at which diesel fuel will flow when cooled under test conditions (15). Both of these temperatures are related to the lowest temperature at which a diesel engine will be able to operate. As can be seen in Table 2.4, the pour point and cloud point are both higher for biodiesel fuel than for gasoline-based diesel, indicating that biodiesel will tend to gel at higher temperatures than diesel, causing engine problems.

2.6 HIGHLIGHTS OF THE LITERATURE

- The purpose of the transesterification process is to lower the viscosity of the oil.
- Methyl and ethyl esters of vegetable oils have several outstanding advantages among other new renewable and clean engine fuel alternatives.
- Biodiesel on its own appears to be easily biodegradable and not harmful to organisms.

- Apart from direct assessment of the engine emissions, environmental impact is also determined by performing life cycle analysis.
- Life cycle analysis is used to evaluate environmental impact and potential factors related to product life cycle energy balance, including raw materials, production, consumption, and waste utilization. Fuel life cycle analysis starts with raw material extraction stage and ends with fuel consumption in vehicle engine.

  [Life cycle analysis demonstrates the additional quantity of energy required to turn the energy present in the raw materials into useable energy of the fuel.]
- Standards and quality control in the manufacture and distribution of biodiesel are being developed to assure that reliable and consistent fuels are supplied to users.
- Straight vegetable oils pose problems when subjected to prolonged usage in C.I. Engines like smoke emission, injector coking, and more engine deposition, ring sticking and thickening of the lubricant. The problems are due to high viscosity, low volatility and polyunsaturated characteristics and results in larger fuel drop sizes and decrease in fuel air mixing rate, causing improper combustion. So, Vegetable oils should be modified to get better performance by different process like preheating, transesterification etc.
- Biodiesel could be used as an environmental friendly fuel in existing diesel engines without substantial hardware modifications.

2.7 CARDANOL OIL AS ALTERNATIVE FUEL

2.7.1 General

This sub chapter covers topics related to cashew plant, nut, and its extracts in the field. These are: cashew agronomy (2.7.3), sections and breeding (2.7.4), fruit set and fruit development (2.7.5), cashew nut processing (2.7.6), Cashew Nut Shell Liquid and its extraction (2.7.7), extraction of cardanol and cardol from CNSL (2.7.8),reason for using cardanol as alternative fuel (2.7.9) & objectives of the present work (2.7.10).

2.7.2 Objectives of growing cashew

The first cashew plantations in many countries were established by the forest departments as an easy way of afforestation. Cashew trees in India were planted for the protection of coastal dunes, sometimes in combination with wasteland recovery [4], almost exclusively on poor soils unsuitable for other crops. In Brazil, plantations exist on more than 40,000 ha. In the countries south of the Sahel with 600-800 mm annual rainfall, cashew is important as a tree to counterbalance desertification. Table 2.5 shows cropping systems in different countries [Typical systems are shown in Plates 2.10-2.13 in page numbers 77&78]. Yields are very low, except for Kerala where more than 1000 kg/ha are achieved because of good soil and enough water. Reasons for low yields lie in no genetical improvement, use of unselected planting material, poor management, poor soils and unstable climatic conditions.

2.7.3 CASHEW AGRONOMY

2.7.3.1 Soils and climate.

Cashew suffers from its image of thriving on the poorest soils where no other crops can give an economic return. As a result, the worst soils are chosen for cashew. The yield potential has never been evaluated on good soils. In typical poor cashew sites yields are low, even with good genetic material. The interdependence of soil conditions and water availability has been confirmed by several authors. Venugopal et al (1991) [65], stated that temperature, humidity and sunshine hours prevailing in different cashew growing regions in India do not appear to influence the yield of cashew as compared to rainfall distribution. The criteria listed in Table 2.5 represent only the most suitable conditions.

Table 2.5: Cropping system and yield of cashew in selected countries [4]

Country	Plantation size (ha)	Spacing (m)	Objective	Inter-crops	Yield (kg)	Author
Mozambiqe	Plantation: farmers 0.3	12 x 12	Fruits	y	100-150	Ohler (1979) NOMISMA (1994)
Senegal	Forest >50 ” ” 1 ha Farmers	3x3,contour 1m in rows 3 x 3 12x12, 5x2	wind breaks, village wood fruits	N Y N Y	100-150 <200 100-150 400-500	Behrens (1988) Ohler (1979) RUDECO (1989)
Tanzania	Farmers<1	12 x 12, 14 14	Fruits	Y	400-500	Lamboll et al. (1993)
India Kerala Karnataka Tamil Nadu Tripura Other	Farmers	7x7, 9x9, 7.5x7.5, 10 10	- fruits –waste land recovery –erosion control	Y*	348 1058 336 126 100 221	Ohler (1979) Mathew (1982) Sarkar et al. (1989)

*Intercropping is advised in the first two years after establishment

Cashew can grow beyond these and even on laterite soils – provided there are no crusts with explosives to make them permeable for cashew plantings. It also tolerates shallow soils and altitudes up to 1000 m. However, it will not tolerate stagnant water or arid conditions (mean annual rainfall<600 mm) without supplementary water supply.

Table 2.6 Criteria for land suitability classification for cashew [4].

	Characteristics	**Suitable conditions**
Soil	Soil texture (surface)	Fine and – sandy loam – silt loam
	Soil texture (subsoil)	fine loamy – coarse loamy
	Coarse fragments in the soil	<20%
	Soil depth	>90 cm
	Salinity	<1 mmhos/cm
	Soil reaction	Ph 5.6-7.3
Topography	Slope	<5%
	Rockiness	<10% of rock exposed surface
	Stoniness	<3%
	Altitude	<600 m
Drainage	Water table dry season	2-6 m
	Water table dry rainy season	1.5-4 m

Detailed land classifications were made by Mishra (1985) for Orissa (India) and by Zech et al. (1992) for Senegal. Five site classes were determined, depending on soil and rainfall. Unsuitable soils (not mentioned in the table) are all soils with low depth (<90 cm), stagnant water during the rainy season, laterite crusts that reduce the potential rooting volume and soils with >42% clay and high bulk density (>1.95 g/cm^3).

Field studies in Senegal confirmed that available water was the limiting factor for cashew growth, despite low soil fertility. The annual precipitation and the potential root depth are significantly related to growth and Krebs concluded that soil depth should be 220 cm under precipitation of 600 mm/year to a minimal depth of 90 cm under 1400 mm/year (Table 2.6). Acute deficiencies in mineral nutrition were not found in the cashew trees, although the above-mentioned soil types are not regarded as particularly fertile.

2.7.3.2 Field establishment

Direct sowing

Direct sowing in the field is possible if the annual rainfall is above 800 mm/year. Planting holes (30x30x30 cm) can be dug before the rainy season to allow water to be held while it infiltrates. Top soil mixed with manure (if termites are not attracted by organic matter) should be filled in the hole. In fertile sandy loam soils this is not necessary. Usually 3 seeds are sown per site in uptight positions; the 2 smaller seedlings are removed after a certain period, depending on the growing conditions, but at the latest before the next rainy season.

Planting

Successful transplanting of cashew is possible, even if they were not sown in containers. The success rate of transplanting bare rooted seedlings varies with the age when it is done. The best results were obtained 11 month after sowing with shoots that had been cut back to half or to a third of their original length (Hassan et al 1957).see Table 2.8. Today, cashews are sown mainly in plastic containers or tubes with a diameter of 6-8 cm and length of 20-30 cm (plates 8). Transplanting is done after 2-3 months, except for grafted seedlings which are transplanted after 4 months, without major setbacks. The water supply should not be interrupted during the 2 weeks immediately following the transplanting.

Spacing

Spacing of cashew for fruit production should consider root growth and canopy growth and should not be too densely planted depending on the site. On good sites roots grow 4-6m from the stem in $2^1/_2$ years, extending outwards about twice as far as the canopy itself (Ohler 1979, Satpathy et al. 1986). The number of trees/ha varies with the objective and conditions and range from 42 to 2500. Mathew (1982) favours high initial densities (1000 trees/ha) for early high yields/unit area, followed by selective thinning from the seventh to the twelfth year with a final density of 200 trees/ha. Ohler (1979) supports this. This method might be good for plantations, but farmers do not cut productive fruit trees. Therefore the current recommendation on farmers fields in Tanzania is a spacing of 14m x 14m combined with intercropping (ODA 1995).

2.7.3.3 Interventions

Protecting cashew plantations

Young cashew trees are very vulnerable to damage by animals. In areas with a pronounced dry season they are often the only green plants in the field and therefore an easy target for wild and domestic animals. The Senegalese-German Cashew Project (PASA) used barbed wire fences to protect the fields, with a cost of 70000 FCFA/ha (appr. 240 US$) for a 4 ha plantation. The high cost finally stopped this way of protection and farmers were urged to use fences made from local material (Table 2.9). Vegetal fences from different plant species are also recommended as cheap and efficient protection for cashew plantations in India, to be preferred to barbed wire or trenches.

Fertilization

Cashew responds well to fertilizers or if provided ecological conditions are adequate. In a fertilizer trial in Senegal on 20 year old trees with 600mm rainfall, no reaction could be found to several doses of NPK applied at beginning of the rainy season. On trees growing on poor soils fertilizer certainly has a positive effect. The findings from (Ghosh et al. 1986) states that the nut quality was improved, interesting for a processor has it could increase their margin. The dosage depends on the site conditions and has to be determined for each locality. Mathew (1982) suggests applying recommended fertilizer dosage on intercrops and adding the quality needed for cashew, as farmers rarely fertilise the cashew trees alone.

Table 2.7 Protection of Young cashew trees with local Material Source: Ohmstedt (1991b) [4]

Method	Comments
Individual Protection	
Gambions made from branches, 70-90 cm high, 40-45cm diameter.	Too dense, no air circulation, seedling suffering, termites.
Thorny branches around the seedling fixed like a tent.	Cheapest method, good protection.
Thorny branches around the seedling fixed on supporting sticks.	Better than above, because fixed in the soil.
Circle planted with 10-15 Euphorbia balsamifera Ait.	90% cashew survival.
Life hedges around the field, immediate protection	
Euphorbia balsamifera cuttings planted in one row, 15cm between plants, with support.	98% recovery, 80-120cm high, 70-75 cm deep.
Euphorbia balsamifera cuttings, one row, Agave sisalana one row.	Combination improves protection.
Jatropha curcas one row.	99% recovery on light soils, good protection after 1 year
Jatropha curcas one row, Agave sisalana one row,	Combination improves protection
Life hedges around the field, protection after 2-3 years.	
Agave sisalana one row.	95% recovery, 35-70cm high, 30-85cm deep
Agave sisalana one row, Parkinsonia aculeate L. one row.	Combination improves protection.
Parkinsonia aculeate one row.	88% survival, 42cm high 60-12cm deep
Zizphus mauritiana Lam. In one row.	Preferred by farmers, law. Recovery (42%) 20cm high.

2.7.4 SECTIONS AND BREEDING [4]

The priority in cashew section is to find germplasm having the capacity to yield as many nuts as possible of an acceptable size and above average kernel content under specific conditions. This implies that a tree (clone, line, variety) that does well under specific conditions may not be as good under other conditions. Therefore it is important to select within the environment where the cashew trees will be grown – from healthy high yielding trees.

Table 2.8 Parameters for the selection of mother trees (Manoj et al.1983)

Parameter	Indicators or minimum requirements
Growth	Height, girth, canopy spread , compactness, (leaf area)
Flowering	Duration (short or long), period (early or late), panicles/canopy area, flowers/panicle,% perfect flowers, "high" fruit set
Nut production per tree	Depends on size of tree, Number of nuts/panicle Better yield for CGCA*>250g/m^2
Nut size	>5g, better 6 g or more
Nut shape	Regular, flat, no hollows
Kernel content	>25%, better>30%
Protein content	18-40%, not essential
Disease resistance	Powedery mildew. Anthracnosis
Pest tolerance	Helopeltis, spp
Apple qualities	Weight, colour, shape, juice content, sugar content, taste.

* CGCA= Canopy Ground Cover Area

The simplest section method is to throw the nuts in water and to select only those that sink. Auckland (1961) found that nuts with a density of >1.025 g/cm^3 (sinking in a solution obtained by dissolving 71 g sugar per liter of water) germinated faster, had a higher survival rate and produced more vigorous plants and more flowers in the first season than nuts below this density. The canopy ground cover area (CGCA) gives a better indication of performance than the nut yield/tree then current descriptions (see table 2.9).

Table 2.9: Characteristics of selected cashew varieties [4]

Location	Origin	Age (year)	Mean Yeild/tree (kg)	Nut weight. (g)	Kernel content (%)	Yeild/ha (kg)	Kernels/Ib	Comments
Kerala	Hybrid	15	11.72	10.8	-	-	-	big nut size
Baptala[2]	Selection	33	57.82	4.6	28	11560	365	big nut size
Andhrapradesh[2]	Selection	33-48	13.57	5.0	27	2710	335	big nut size
Andhrapradesh[3]	Hybrid	25	19.00	4.0	26	-	435	Released varieties
Maharashtra[3]	-	28	23.00	6.0	31	-	245	Released varieties
Tamilnadu[3]	-	17	7.40	5.0	20	-	454	Released varieties
Karnataka[3]	Selection	25	19.00	7.0	31	-	210	Released varieties
Kerala[3]	Selection	7-14	17.14	7.3	26	-	240	Released varieties
Karnataka[3]	Selection	-	6.69	4.5	33	-	305	Selection for high kernel content
Anakkayam[4]	Selection	-	3.29	3.6	46 (39)	-	(280) 330	Selection without CNSL in Kernel
Ullala[5]	Selection	11	14.68	7.0	30	-	215	New released variety
Senegal[6]	Seedling	29	36.48	6.9	-	-	-	Trees-farmers fields

Sources: [1] Nalini et al. (1994a), Reddy et al. (1983), Bhaskara Rao (1989), Nalini et al. (1994b),Kumar et al. (1994), Ohmstedt (1991c).

2.7.4.1 Socio-economic considerations [4]

In most countries cashew is a typical small holder crop. In India vast areas are planted in the frame of soil conservation by the department of agriculture and as a source of income in social forestry and waste land recovery programs (Satpathy 1987, Chopra 1990, Choudhury 1992). As these programs aim to plant vast areas in a short period of time, seed quality cannot be assured.

The greatest limitation to cashew production is the amount of manual labour to harvest the nuts. An experienced worker can collect about 525 nuts/hour (Morton et al). 1972, equal to 2.6 kg for nuts weighing 5 g each. With an average wage of 150 FCFA/hour (in Senegal) and a farm gate price of 100 FCFA/kg (RUDECO 1989), harvesting costs take nearly 60% of the revenue (nuts weighing 8 g each = 4.2 kg/hour = 28%). These figures underline the importance of careful selection of planting material. Bigger nuts reduce harvesting costs. This limitation offers a chance for small holder farmers whose aim is not profit maximization per area of land or per man hour but to raise overall family income. The cashew harvest usually starts during the last 2 months of the dry season, when fresh food becomes rare and money from cash crops dwindles. This indicates an ideal period for additional income! Children and old people can collect apples for direct consumption and nuts for sale without creating harvesting costs.

2.7.5 Fruit set and fruit development [29]

About 10% of the hermaphrodite flowers produce mature fruits, figure 2.3 depicts the flowers and fruits (Purseglove 1968). After fruit set a substantial fruit drop follows in most cases (Table 2.10). Sapkal et al. (1994) studied fruit set and fruit retention on 9 clones in 1985 (550 mm rainfall) and 1986 (595 mm) and found that only 0.7-4.1% of hermaphrodite flowers developed into ripe fruits. They attribute this to poor pollination (fruit set between 9-22%), but the dry weather might also be responsible for these low values. However, there are clonal differences and careful selection can easily increase yield.

Figure 2.3: Fruit development

Table 2.10: Fruit set and fruit drop [4]

Fruit set (% of perfect flowers) and cause	**Fruit drop (% of fruits set and cause)**	**Location**	**Author**
40 low pollination	>77	Australia	Wunnachit & Sedgley (1992)
12-55	51-100	Orissa (India)	(Patnaik et al. 1985).
3-31 low insect populations	34-84 Psychological causes at the initial stage; insect or disease incidence for fruit drop in later stages	West coast of India	Nawale et al. (1984)

The time from fertilization of the ovary to maturity of the fruit depends mainly on the temperature. Rao et al. found a range from 43 days in the later (warmer) season (April, 28^{o}C mean temperature) to 58 days in the early season (February, 24.4^{o}C mean temperature). In the early stage the nut grows faster than the apple and reaches its maximum size about 30 days after pollination. The peduncle (apple) remains smaller during this time and increases only after 35 days, while the nut shrinks by about 10% until maturity (Plates 3 and 4). Kumar et al. (1984) stated that optimum fruit development (ripening) occurred at 70 days after fruit set, without specifying the conditions. Ranganayaki et al. (1993) found that early maturing nuts (40 days, 3.39g/nut) were smaller than nuts that matured at 50 days (4.65g/nut) or 60 days (5.38 g/nut). It seems that, according to the method described, the nuts harvested after 40 or after 50 days are not fully mature. This can be explained as due to too early harvesting which is a valid widespread practice on commonly owned trees.

2.7.6 CASHEW NUT PROCESSING [4, 67, 68]

The cashew tree is evergreen. It grows up to 12 metres hight and has a spread of 25 metres. Its extensive root system allows it to tolerate a wide range of moisture levels and soil types, although, commercial production is advisable only in well-drained, sandy loam or red soils. Annual rainfall needs to be at least 889mm (35 inches) and not more than 3048mm (120 inches). Cashew trees are most frequently found in coastal areas.

Figure 2.4: Cashew Fruit

The main commercial product of the cashew tree is the nut. In the main producing areas of East Africa and India, 95% or more of the apple crop is not eaten, as the taste is not popular. However, in some parts of South America and West Africa, local inhabitants regard the apple, rather than the nut kernel, as a delicacy. In Brazil, the apple is used to manufacture jams, and soft and alcoholic drinks. In Goa, in India, it is used to distil a cashew liquor called “feni”. The cashew fruit is unusual in comparison with other tree nuts since the nut is outside the fruit. The cashew apple is an edible false fruit, attached to the externally born nut by a stem. In its raw state, the shell of the nut is leathery, not brittle. It contains the thick vesicant oil, CNSL, within a sponge-like interior. A thin testa skin surrounds the kernel and keeps it separated from the inside of the shell. The primary products of cashew nuts are the kernels which have value as confectionery nuts.

Cashew nut shell liquid (CNSL) is an important industrial raw material for resin manufacture and the shells can be burned to provide heat for the decorticating operation.

4.5.1: Processing overview [67]

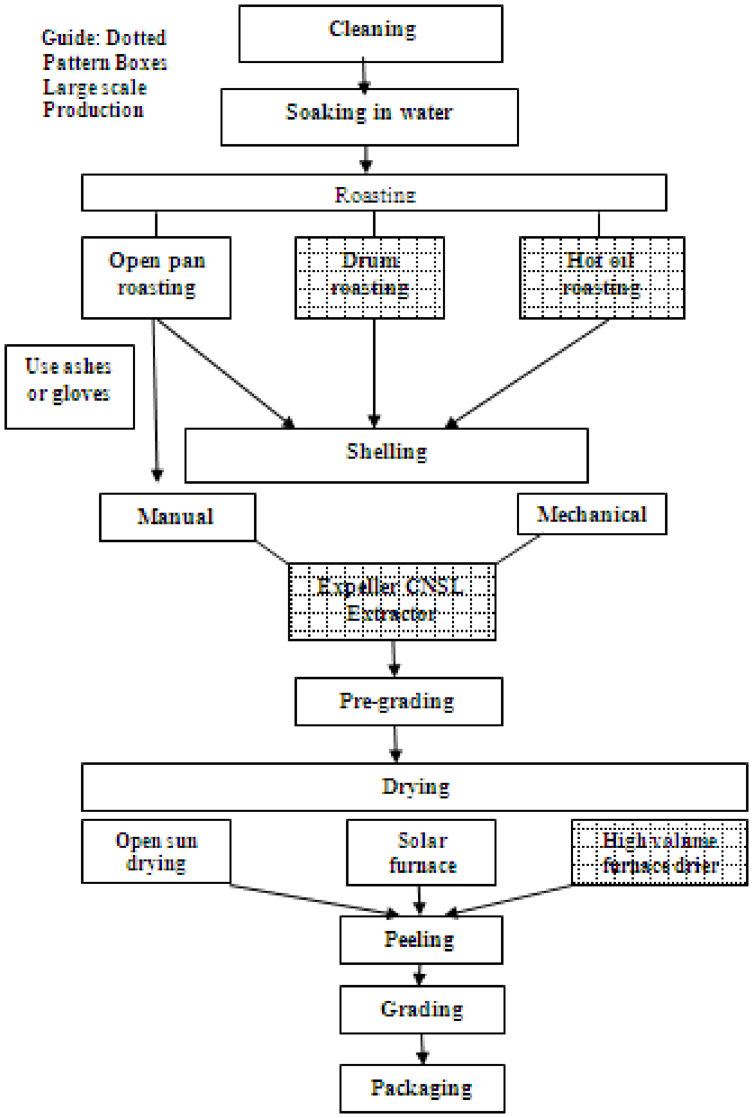


Fig 2.5 Cashew nut processing overview

Traditionally, extraction of the kernel from the shell of the cashew nut has been a manual operation. The nut is roasted which makes the shell brittle and loosens the kernel from the inside of the shell [Figure 2.5 depicts the Cashew nut processing overview]. By soaking the nuts in water, the moisture content of the kernel is raised, reducing the risk of it being scorched during roasting and making it more flexible so that it is less likely to crack. The CNSL is released when the nuts are roasted. Its value makes collection in sufficient quantities economically advantageous.

Figure 2.6 Cashew apple, Nut, Kernel and Cashew shell

If the nuts are being manually shelled, gloves need to be used or alternatively, the nuts should be tumbled in sawdust or ashes to absorb the liquid coating which has a harmful affect on the skin[Figure 2.6 depicts, processing stages like, nut separation-cashew nut-cashew kernel-shell].

The shell can be cracked either manually, using a hammer, or mechanically. Manually operated blade openers (as listed in the supplier's section) are relatively inexpensive; however the more successful mechanical methods depend on the nuts having passed through the 'hot oil' CNSL extraction operation. Care must be taken not to break or split the kernel at this or subsequent stages as whole kernels are more valuable than broken ones. Once the kernel is removed from the shell, it is dried, the testa is peeled off and the kernel is graded. Figure 2.5 gives an overview of cashew nut processing and the various choices in methods. Figure 2.6 depicts, a photograph of cashew apple, nut, kernel and cashew shell.

2.7.6.2Cashew nut processing procedure

Cleaning

All raw nuts carry foreign matter, consisting of sand, stones, dried apple etc. The presence of foreign matter in the roasting operation can be avoided by cleaning the nuts. The raw nuts can be sieved by hand using a ¾ inch mesh sieve.

Soaking

The next stage is to soak the nuts in water to avoid scorching them during the roasting operation. This can be done by placing the nuts in a 40-45 gallon drum or vat and filling it with water until all the nuts are covered. After being left to stand for about ten minutes, the water should be drained off via a plug near the base of the drum. The nuts should then be left for periods of not less than four hours in order to allow the water left on the surface of the nuts to be absorbed. The process of covering the nuts with water, draining and standing should be repeated with the same nuts about three times until a moisture content of 9% is reached. Where the production output runs from 2-10 tons of nuts per day, a simple cleaning and conditioning arrangement can be used. Two people open the sacks of harvested nuts on a stand and clean the raw nuts as they are moved along a flat sieve, to two vats which are used for storage until the soaking process begins. Two vats are useful because one can be emptied while the other is being filled.

Roasting

The application of heat to the nut releases the nut shell liquid and makes the shell brittle which facilitates the extraction of the kernel when breaking the shell open. Three methods of roasting exist: open pan, drum roasting and the ‘hot oil’ method. The latter is more suitable to medium-scale operations with associated higher equipment costs and viability of CNSL collection.

a) **Open pan**:

An open, mild steel, circular dished pan of around 2 feet in diameter is supported on a basic earth fireplace. When heating, 2-3lbs (1kg) of nuts are placed on the pan at one time and stirred constantly. The CNSL starts to exude and then ignites. This produces a long flame and black smoke. After approximately two minutes, the pan is dowsed and the charred, swollen and brittle nuts are thrown out of the pan. The moisture evaporates quickly leaving the nuts ready for shelling.

b) **Drum roasting:**

The idea of continually feeding the nuts into a rotating drum over a fire developed from the pan method. A slight horizontal slope in the mounting ensures the movement of the nuts through the drum. The drum is pierced so that the flames touch the nuts and the smoke is controlled by a hood and chimney arrangement. The nuts are dowsed using a continuous spray. This process is further modified by using the heat from the burning CNSL being harnessed to roast the nuts some more. The roaster consists of a contained helical screw which moves the burning nuts at a controlled rate. The design is a distinct improvement, with little fuel being consumed and there being greater control on the roasting time.

c) **‘Hot oil’ method:**

The principle employed in this method is that oil-bearing substances i.e. the shells, when immersed in the same oil at high temperature, will lose their oil, thus increasing the volume of the oil in the tank. For this method, conditioning becomes important. The equipment consists of a tank of CNSL heated to a temperature of 185-190°C by a furnace underneath and a wire basket used to hold the nuts for immersion into the tank. The depth of the basket must be sufficient so that the rim remains well above the oil during the roasting. Immersion time can range from 1½ to 4 minutes. About 50% of the liquid is extracted from the nuts. Draining trays are needed at the end of the tank for the roasted nuts to dry and the residue oil can be returned to the tank. Caution must be taken not to heat the tank to over 200°C because at this point polymerization of the CNSL takes place. The temperature can be maintained by continuous firing. The tank should be emptied and cleaned after each day's roasting. The life of a tank made of an 1/8th inch thick mild steel plate should exceed one and a half years and can be constructed locally with welding facilities.

Shelling

The objective of shelling is to produce clean, whole kernels free of cracks. In India, this operation is being carried out manually. Other countries have difficulty in competing with the great skill and the low wages of the Indian workers. Therefore, India has enjoyed a virtual monopoly of cashew processing for a long time. Manual shelling is still relevant to the small-scale processor, although a close look at the mechanical option is advisable in all cases.

a) Manual:

In the manual shelling process, the nuts are placed on a flat stone and cracked with a wooden mallet. As mentioned above, because of the residue CNSL, wood ash for covering the shells or gloves are required. An average sheller can open one nut in about six seconds or ten nuts per minute. In an eight-hour working day, this amounts to about 4,800 nuts or about 5kg of kernels. At an extraction rate of 24%, this quantity corresponds to about 21kg of raw nuts per day or about 7 tons per year. However, experienced shellers in India can produce around half as much again, with a quality of 90% whole kernels.

b) Mechanical:

The most successful mechanical shellers work on nuts which have previously passed through the 'hot oil' process. A semi-mechanized process that has been used predominantly in Brazil uses a pair of knives, each shaped in the contour of half a nut. When the knives come together by means of a foot operated lever, they cut through the shell all around the nut, leaving the kernel untouched. Two people work at each table; the first cuts the nuts and the second person opens them and separates the kernel from the shell. Daily production is about 15kg of kernels per team. The first mechanised shelling system, Oltremare, is also based on two nut-shaped knives. The nuts are brought to the knives on a chain, each nut in the same position to fit between the knives. The nuts are pushed between the knives and cut. The chain itself has to be fed manually. After coming together, the knives make a twisting movement, thus separating the shell halves. The shelling machines of the Cashco system are also chain fed but the nuts are automatically placed in the right position. The shelling device has two knives that cut the sides of the nut and a pin, that is wedged into the stalk end of the nut, separates the shell halves. The advantage of this system is a fully mechanised operation with an output of about 75% whole kernel qualities. Nuts smaller than 15mm cannot be processed. Centrifugal shellers use a system which is simple and enables a continuous flow. A rotary paddle projects the shells against the solid casing and the impact cracks open the shell without breaking the kernel. All sizes of nuts can be processed by this method, however, it is necessary to grade the nuts into four or so group ranges because a different rotary speed is used for the various size groups. The percentage of whole kernels produced is around 75%. By preparing the shells with grooves and weakening the strength of them before the operation begins, the percentage can be increased. The speed of the rotor can thus be turned down and the risk of damaging the kernels is reduced.

c) Separation:

After shelling, shell pieces and kernels are separated and the unshelled nuts are returned to the shelling operation. Usually blowers and shakers are used to separate the lighter shell pieces from the kernels. The greatest problem is to recover small pieces of kernel sticking to the shell. This is usually done manually from a conveyor belt used to carry all the sorted semi-shelled nuts.

2.7.7 CASHEW NUT SHELL LIQUID (CNSL) AND ITS EXTRACTION [41]

Cashew nut shell liquid (CNSL) is a by-product of cashew industry in India, which is a major earner of foreign exchange. CNSL is contained in the soft honeycomb structure between the outer shell and the kernel of the cashew nut. The cashew nut tree (Anacardium Occidentale Linn, Hindi, Kaju) belongs to the natural order Anacardiaceae, like the Bhilawan tree and grows at altitudes below 1000 ft. along the West and Eastern coasts of India. It is extensively cultivated in Brazil, East Africa, Tanzania, Mozambique, Madagascar, Philippines and other tropical regions. In India it is grown in the states of Kerala, Tamil Nadu, Karnataka, Andhra Pradesh, Maharashtra, Orissa, West Bengal, Assam and Goa.

The cashew fruit has a kidney-shaped nut 1 to 1.5 inches long. The nut is attached to the end of a fleshy receptacle or enlarged peduncle of the fruit, which is commonly known as cashew apple. This is pear shaped or rhomboid-to-oval having 2-4$^1/_2$ inches length and is bright yellow to red with a waxy skin. Pericarp of the nut consists of coriaceous epicarp, spongy mesocarp and stony endocarp. The mesocarp consists of a honeycomb network of cells which gives cashew nut shell liquid.

2.7.7.1 Production of cashew nut shell oil. [48]

The cashew nut industry is located on the west coast of India, the main areas being Quilon, Calicut and Mangalore. The actual production of cashew nut shell oil is about 15,000 tonnes, while the potential is about 60,000 tonnes and the consumption is around 11,000 tonnes by the paints, varnish and other industries. Exports of CNSL are around 9000-10,000 tonnes annually.

Out of the several processes used for the manufacture of CNSL, the hot oil process is quite economical. The other methods are; i) Kiln, ii) Expeller, iii) Drum roasting, iv) Solvent extraction, v) Super-heated steam and vi) Dielectric heating at radio frequency (RF)’. These methods have their own advantages and disadvantages and give CNSL with different characteristics; for example, CNSL obtained by solvent extraction gives higher range of acid and iodine numbers (A. V. 94-107; 1. V. Wijs 270-330) as against the one obtained from roasted cashew nuts (A. V. 5-20; 1. V. Wijs 200-300).

2.7.7.2 CNSL Composition [41, 48, 67]

The commercial CNSL contains a mono-phenol and dihydric phenol as major constituents and minor amounts of 6-alkyl salicylic acid (anacardic acid). The presence of anacardic acid only in small amounts is due to the fact that most of it gets decarboxylated at the temperature of extraction of CNSL. The resulting mono-phenol is a very useful industrial raw material for the manufacture of lacquers and varnishes. While the heat extracted liquids, therefore, do not contain more than 16 per cent, the liquids obtained by pressure extraction or solvent extraction are known to contain up to 70 per cent of anacardic acid, cardol and cardanol is not a homogeneous diolefin, but is a mixture of olefins of different degrees of unsaturation. By using modern chromatographic techniques it was discovered that cardanol (hydroxyl value 180-200), has the saturated component 5.4 per cent, mono olefin 48.5 percent, diolefin 16.8 per cent and triolefin 29.3 per cent. Using the modern NMR technique Gedarn, Sampathkumaran and Sivasamban have shown the presence of higher proportions of diene and triene components in 6 methyl cardol and cardol than in Cardanol. The average side chain unsaturation in the case of cardanol. 6-methyl cardol and cardol amounts to 1.5, 2.0 and 2.0 double bonds per mole respectively. By the use of gas-liquid chromatographic methods the component phenols in the technical CNSL have been determined with much improved precision. This method is quicker to operate than any preceding methods. The analysis shows that CNSL contained 82 per cent anacardic acid; 13.8 percent cardol, 2.6 percent 2-methyl cardol and 1.6 percent cardanol.

While discussing the chemistry of cardanol, it is interesting to consider the condensation reactions between phenol and formaldehyde, phenol and hexamine and phenol and styrene.

2.7.7.3 Condensation reaction between phenol and formaldehyde.

Phenol can be condensed with formaldehyde to obtain novolaks and resoles respectively, depending on the ratio of phenol to formaldehyde and on the use of acid or alkaline catalysts. Similar reactions take place with CNSL and cardanol. The structure of the novolaks and resoles are as follows.

2.7.7.4 Condensation reaction between phenol and hexamine.

The important condensation reaction of phenol and hexamine is as follows.

13 C6 H5 OH + 2(CH2)6N4 – (CH2010 (C6H3OH) 11 (CH2C6H4OH) 2 +8NH3

Hardening of the phenolic appears to be due to the formation of complex structure, containing both secondary and tertiary amine bridges. On heating, these break down in the presence of excess phenol with the evolution of ammonia, leading to nitrogen free resin with methylene bridges. Similar reactions take place with CNSL and cardanol.

2.7.7.5 Reaction between phenol and styrene

Styrenated CNSL is prepared by reaction of styrene with CNSL hexamine condensate leading to a polymer of the following give structure. Styrenated cashew nut shell liquid resins which can also be oil-modified, air dry rapidly and possess satisfactory alkali and water resistance properties.

2.7.7.6 Cashew Testa

Cashew testa is the outer skin of cashew kernel which contains about 25 per cent of tannin material and 11 per cent of non-tannins. The tannins consist of D-catechin, gallic acid and leucocyanidin, a significant tannin precursor, while the non-tannins consist of quinic and caffeic acids. These tanning materials have shown similar properties to that of imported wattle bark tannin used in leather industry.

2.7.7.7 Cashew kernel

The cashew kernel covered with testa is contained in a shell $^1/_8$ inch thick, which forms about 67 percent of the whole cashew nut, the remainder being the kernel. Cashew kernel yields about 42.2 per cent of a glyceride oil of the following fatty acid composition: oleic, 59.60; linoleic, 19.62; palmitoleic, 11.14; palmitic, 0.89% ofeter each figure and stearic, 8.75 %. The composition of the cashew kernel is very similar to that of sweet almond and constitutes a very nutritive and concentrated food. The kernel contains larger percentage of protein (20 per cent) and is rich in calcium, phosphorus, iron and vitamin A. vitamins B_1, and B_2 are also present to a small extent. Recently cashew nut neutral lipids, glycolipids and phospholipids were isolated by silic acid chromatography. Each lipid class had characteristic fatty acid distributions with phospholipids being higher in lonoleic acid.

To round up, a few articles on cashew shell liquid derivatives, minor constitutes of cashew nut shells, manifold uses of cashew nut shell liquid chemical aspects of CNSL, isolation of pure cardol from CNSL, chemotherapeutic investigations on CNSL extract etc., have appeared periodically; This brief introduction gives a bird’s eye view of the multi-faceted work carried out both in India and abroad on CNSL in respect of extraction, refining and utilization in surface coatings and other fields.

2.7.8 EXTRACTION OF CARDANOL AND CARDOL FROM CNSL. [48, 67]

A process has been developed by F.S Kerr and Company and Gokhale, G.D, for the separation of the principal constituents of cashew nut shell oil (CNSL) (Indian Patent 27720;October 2, 1940).It is known that CNSL mostly contains two important constituents, namely, i) anacardic acid and acidic substance; and ii)’Cardol’- a non acidic material . The main objectives of this invention are (i) to provide a simple and economical method for isolating the so called cardol complex from anacardic acid, (ii) to provide an improved method of extraction of the decarboxylated product ‘anacardol’ or otherwise known as ‘cardanol’ from cashew nut shell liquid, iii) to provide a method of forming and extracting cardanol from CNSL by direct treatment of the oil and not by the indirect route of separation of anacardic acid and then treating the same, (iv) to provide a simple laboratory apparatus for the extraction of the above materials, which may ultimately be produced on a commercial scale and (v) to indicate the commercial application of anacardol.

2.7.8.1 Separation of acid constituents from CNSL [36]

A process for the separation of acid constituent from cashew nut shell liquid or hydrogenated cashew nut shell liquid has been disclosed in 1945 by General Foods Corporation of New York, United States of America (Indian Patent 34671; April 23, 1945)[8]. The prime object of this invention is to provide a process by which the acid constituents of cashew nut shell liquid (CNSL) are easily and economically separated from CNSL without encountering any of the disadvantages of the prior processes, namely the basic lead hydroxide method or the sodium or other alkali method.

2.7.8.2 Cashew producing states in India [4]

During the eighties, with the implementation of a World Bank-aided project in four states, namely, Andhra Pradesh, Kerala, Karnataka and Orissa, the farmers became aware of the horticultural practices in cashew cultivation **[**Table 2.11depicts, Major Cashew producing states in India]. The production, which was one-lakh tones during 1983-84, rose steadily to above 4 lakh tones in the nineties.

Table 2.11: Major Cashew producing states in India

States	Area in hectares	Production in tonnes
Kerala	120000	100000
Maharashtra	103500	60000
Andhra Pradesh	108600	45000
Orissa	87000	35000
Karnataka	80500	30000
Tamil Nadu	52000	25000
Goa	52000	25000

2.7.8.3 Global scenario-World production of Cashew nuts:

Around one million tonnes per annum cashews are grown around the world, chiefly within a band 10 degrees north and south of the equator. Major producers are located in Brazil, India and Africa.

- Cashew nut shell liquid is used in almost every automobile in the world. It provides heat resistance as an additive in brake linings. The product has been around since the 1920s or 30s.
- Worldwide consumption of cashew nut oil by the auto industry is estimated to be about 25000 tonnes per year.
- Palmer is the largest buyer worldwide of cashew nut shell liquid, which it processes further via a separation process.
- Cardolite is the largest buyer in North America

Table 2.12 Chemical analysis of the Cashew Nut Shell Liquid [67]

I	**Gross Calorific Value :**	**5056 Kcal / Kg**
II	**Proximate analysis (% weight)**	
	Moisture :	**8.85**
	Volatile matter:	**68.03**
	Ash :	**2.00**
	Fixed Carbon :	**21.12**
III	**Ultimate Analysis**	
	Carbon :	**46.08**
	Hydrogen :	**3.88**
	Nitrogen :	**0.21**
	Sulphur :	**NIL**
	Mositure :	**8.85**
	Ash :	**2.00**
	Oxygen :	**38.98**
IV	**Bulk density :**	**0.4430g/cc**
V	**Ash Chemical composition (% by weight)**	
	Silca (Si02) :	**61.83**
	Iron Oxide (as Fe203) :	**3.99**
	Aluminium Oxide :	**1.99**
	Calcium Oxide (as CaO) :	**25.64**
	Magnesium Oxide (as Mgo) :	**1.88**
	Sodium Oxide (as Na20) :	**0.65**
	Potassium (as P205) :	**Traces**
	Sulphate (as P205) :	**Traces**
	Phosphate (as P205) :	**Traces**
VI	**Ash Fusion Characteristics**	
	Intial defoamation temperature (T1) :	**840**
	Herrisphericla temperature (T2) :	**920**
	Fusion temparature (T3) :	**1010**

2.7.8.4 Cardanol extraction

According to the invention [48], CNSL is subjected to fractional distillation at 200° to 240°C under reduced pressure not exceeding 5 mm of mercury in the shortest possible time which gives a distillate containing cardol and the residual tarry matter, for example, in the case of a small quantity of oil, say 200 ml/ the distillation period is about 10 to 15 minute. When CNSL is distilled at a reduced pressure of about 2 to 2.5 mm. mercury, the distillate containing anacardol and cardol distils firstly at about 200°C to 240°C.

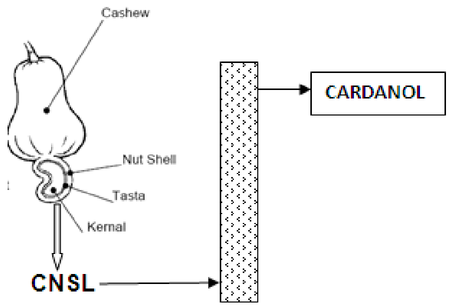


Figure 2.7 Diagrammatic representation of production of Cardanol

This first distillate is then subjected to a second distillation under the same identical conditions of temperature and pressure when the anacardol distils over at a temperature of 205°C to 210°C and the cardol distils over at a temperature of 230°C to 235°C. The first step of the process is to get the decarboxylated oil by heating the oil to a temperature of 170°C to 175°C under reduced pressure of 30-40 mm. mercury. The next two steps are the same as above for the production of both cardol or cardanol and anacardol. Figure 2.7 depicts the diagrammatic representation of production of cardanol.

DR-CNSL - Double Refined Cashew nut Shell Liquid. The Cashew Nut Shell Liquid (CNSL) obtained by pyrolysis. It mainly consists of two naturally produced phenolic compounds: Anacardic acid 90% cardol or cardanol 10%. Figure 4.3 shows the chemical structure of CNSL.

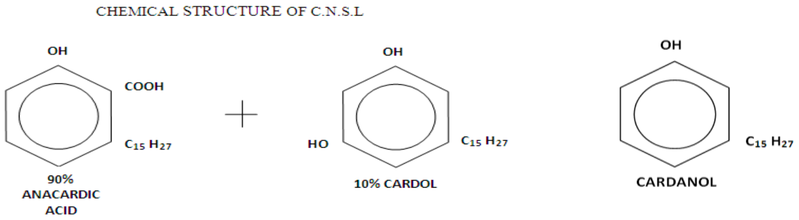


Figure 2.8 Chemical structure of CNSL

Cardanol obtained by pyrolysis from DR-CSNL oil was utilized for testing purposes. Cardanol is a naturally occurring phenol manufactured from CNSL. It is a monohydroxyl phenol having a long hydrocarbon chain in the Meta position and is shown in Figure 2.8.

Table 2.13 Cardanol Specifications [39, 67]

PARTICULARS	GRADE-1	SPECIAL GRADE
Structural Formula	OH $C_6H_4C_{15}H_{27}$	OH $C_6H_4C_{15}H_{27}$
Density	0.9272-0.9350	0.9272-0.9350
Viscosity at 30°C	55.65(CP)	55.65(CP)
Melting point (Less than)	50°C	50°C
Volatiles Maximum as per IS 101-1964	1%	1%
Ash Contents	Negligible	Negligible
Iodine Value IS 548-1964 (Catalytic Method)	Min 250	Min 275
Acid Value	Max 5	Max 5
Colour Gardener (Freshly Distilled)	Light Brown	Pale Straw
Moisture	1% V/V	1% V/V

2.7.9 REASON FOR USING CARDANOL OIL AS ALTERNATIVE FUEL

- ✓ It is renewable.
- ✓ It contains very good calorific value.
- ✓ Easily produced inexpensively in most regions of the world.
- ✓ The cardanol oil is a byproduct of cashew nut industry and it is new to bio fuel community.
- ✓ Non-edible oil & it is extracted from the cashew nut shell not from the seed.

2.7.10 OBJECTIVES OF PRESENT WORK

In the present work cardanol biodiesel was chosen as a fuel for investigation. From the past investigations, no much work has been reported on the use of cardanol biofuel in diesel engines. Keeping in view the plight of the energy crisis, I have experimented and have used cardanol biodiesel and its blends with diesel for investigation in Single cylinder, VCR, and double Cylinder diesel engines. Experimental investigations have been carried out with following objectives.

- To study the fuel properties of cardanol biodiesel such as specific gravity, kinematic viscosity, flash point and fire point, which influence the combustion and the engine performance and emission characteristics; because the CBD has different physical and chemical properties than the petroleum, based diesel fuel.

- To study the comparison of properties of cardanol biodiesel its blends with diesel oil. For comparison, the same properties of the diesel oil were to be determined.
- To conduct performance and emission characteristics test on stationary single cylinder and Variable compression ratio CI Engines at no load-full load conditions to find the optimum blend of cardanol oil with diesel. To extend the performance emission characteristics studies on double cylinder CI engine to find optimum blend of CBD with diesel.
- To compare the results of performance and emission characteristics of all the CI engines operated with cardanol biodiesel volumetric blends.

Figure 2.9: Cluster of developing cashew nuts about 25-30 days after pollination

Figure 2.10: 5 Year old cashew plantation

Figure 2.11: 20 Year old cashew plantation (12m×12m)

Figure 2.12: Well growing 25 year old cashew tree

Figure 2.13: Cashew Nursery

CHAPTER-3

EXPERIMENTAL WORK

3.1DETAILS OF EXPERIMENTAL SET-UPS

The details of all the experimental set-ups are presented in this chapter. The information about engines and its specifications, instrumentation and controls adopted etc, are described.

3.1.1 Various experimental set-ups used for experimentation

Three different test engines were employed during this test program, as summarized below in Table 3.1. These engines represented a wide range of potential applications for biodiesel fuel. The various components of the experimental set-up are described below. Figures show the layout of experimental set up with instrumentation for the study of performance and exhaust emissions of diesel engines.

Table 3.1 Different test engines employed during this test program

Test NO.	Engine Type	Rated Power HP	Test Type
1	Single cylinder diesel engine	5	Performance and Emission Characteristics of CI Engine with cardanol biodiesel volumetric blends and diesel.
2	Single cylinder VCR diesel engine	5	Performance and Emission Characteristics of Variable Compression Ratio engine (with higher and lower CR) with cardanol biodiesel volumetric blends and diesel.
3	Twin Cylinder diesel engine	10	Performance and Emission Characteristics at various loads Twin cylinder CI Engine operated with cardanol biodiesel volumetric blends and diesel.

3.2 EXPERIMENTATION WITH SINGLE CYLINDER C I ENGINE TEST RIG

In this work the various performance tests and optimization tests were conducted on four stroke single cylinder CI engines manufactured by Kirloskar Company limited. The parameter involved in performance analysis has been measured using the following set-ups.

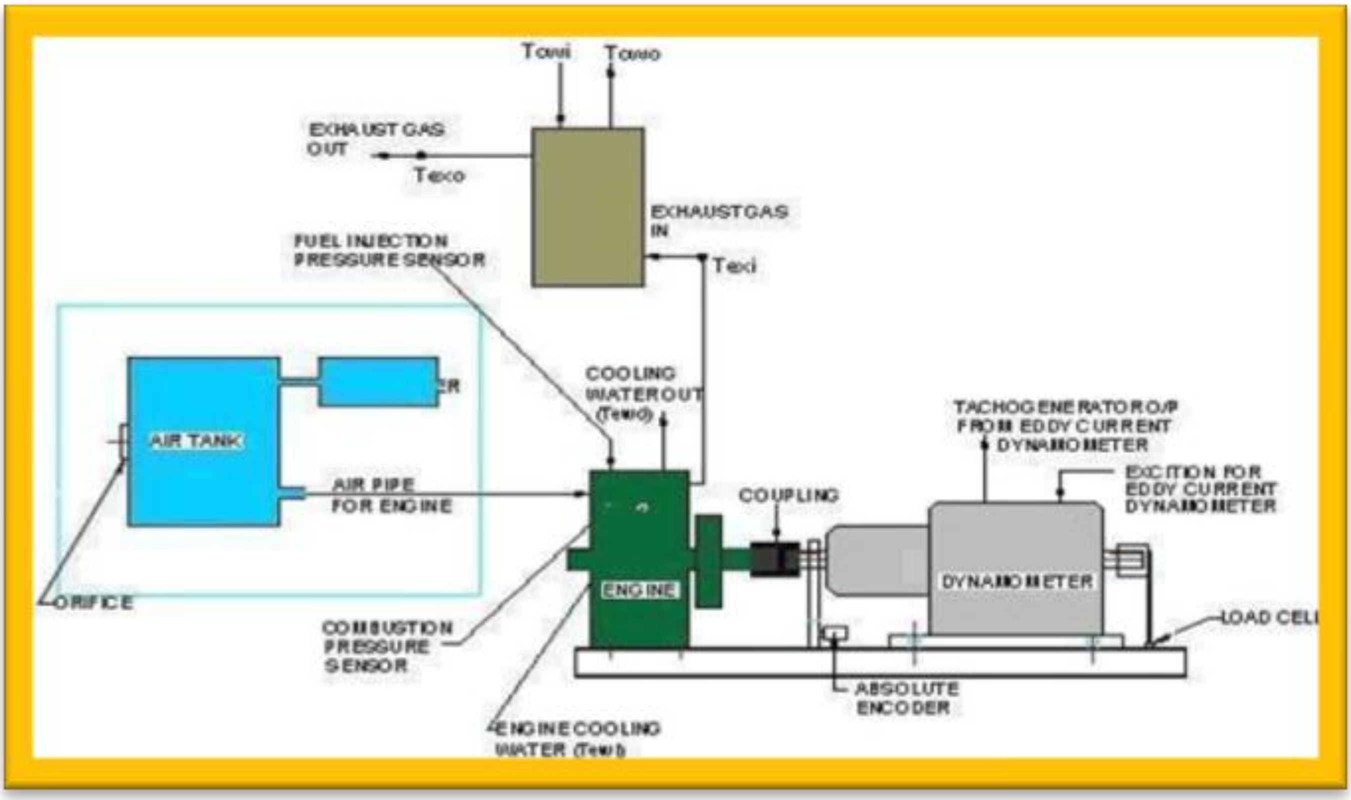


Fig 3.1 Block diagram of the Single cylinder engine test rig

3.2.1 Specifications of the Single cylinder engine

Table 3.2 Engine Specifications of the Single cylinder engine

1. Engine	Diesel,Four stroke, single cylinder, and Constant speed, water cooled
a)Make/model	KirloskerTV-1 At 1500 rpm
b)Rated Power	5.2 kW
c)Bore & stroke (mm)	87.5&110.0
d)Cubic capacity (liters)	0.6615
e)Nominal compression ratio	17.5:1
f)Connecting rod length (mm)	234
2. Dynamometer type	Eddy current175 mm Lever arm at load cell Load dynamometer
3. Fuel flow measurement	Fuel measurement with DPT
4. Air flow measurement	Orifice meter with monometer and DP Orifice diameter 20 mm
5. Water flow measurement	Rotometer
6. Temperature measurement	RTD PT-100 sensors
7. Cylinder pressure measurements	by piezo sensor
8. Crank position / speed	by rotary encoder
9. Fuel injection pressure	by piezo sensor
10. Analysis	Through computer software

3.2.2 Exhaust gas analyzer

An automotive emission analyzer QRO– 402 of QROTECH CO. LTD was used to measure HC, CO_2, CO, O_2 and NOx emissions.

Fig 5.2.Exhaust gas analyzer

3.2.3Measurement system

The experimental set up is fully instrumented to measure the different parameters during the experiments on the engine.

3.2.2.1 Air Flow Measurement

Airflow measurement is done by the conventional method U-tube manometer as well as by Air Intake Differential Pressure (DP) unit present in the control panel. There will be two parallel air suction arrangements, one for a U-tube manometer having the range of 100-0-100 mm and another for pressure differential unit, which senses the difference in pressure between suction and atmospheric pressure. This difference in pressure will be sent to a transducer, which will give the direct current (DC) volt analog signal as output, which, in turn, will be converted into digital signal by Analog to Digital Converter (ADC) and fed to the engine software.

The fuel tank in the control panel is connected to a burette for manual measurement and to a Fuel Flow DP (Differential Pressure) unit for measurement through the computer.

3.2.2.2 Pressure Measurement

A water cooled piezo sensor mounted on the cylinder measured the dynamic pressure and a piezo sensor mounted on the fuel line near the injector measured the fuel injection pressure. The injector nozzle opening pressure was measured externally by standard MICO injector test bed.

3.2.2.3 Engine Speed Measurement

Engine speed is sensed and indicated by an inductive pick up sensor in conjunction with a digital RPM indicator, which is a part of the eddy current dynamometer-controlling unit. The dynamometer shaft, rotating close to inductive pick up serves as an arrangement to send a voltage pulse whose frequency is converted to RPM and displayed by digital indicator in the control panel, which is calibrated to indicate the speed directly in number of revolution per minute using rotary encoder.

3.2.2.4 Load Measurement

The Eddy current dynamometer is provided to test the engine at different loading conditions. A strain gauge type load cell mounted beneath the dynamometer arm measured the load and signals are interfaced with ADC card to give load in kilogram. The dynamometer is loaded by the dynamometer-loading unit situated in the control panel.

3.2.2.5 Other measurements

Fuel consumption was volumetrically measured using metering burette; the consumption was determined by measuring the time for the consumption of a fixed fuel volume. The exhaust gas temperatures were recorded with chromel-alumel thermocouples. The engine was started on neat diesel fuel and warmed up. The warm up period ends when the cooling water temperature was stabilized.

3.3 Experimentation on VCR diesel engine test rig with cardanol biodiesel volumetric blends.

The engine was started on neat diesel fuel and warmed up. The warm up period ends when the cooling water temperature was stabilized. The Kirlosker, engine is one of the widely used engines in agriculture tractors, pump sets, farm machineries and for medium scale commercial purposes. Variable load tests were conducted for 0, 0.8, 1.53, 2.61 and 3.22 kW at a constant rated speed of 1500 rpm, with fuel injection pressure of 190 bars, and cooling water exit temperature of 60^0C. All observations recorded were replicated thrice to get a reasonable value. The performance characteristics of the engine was evaluated in terms of break thermal efficiency, break specific fuel consumptions (BSFC), break specific energy consumptions (BSEC) and emission characteristics in terms of smoke unburnt HC, CO and exhaust temperature. These performance and emission characteristics were compared with the results of base line diesel.

3.3.1 Experimental set up

The various components of the experimental setup are described below. Figure 3.3 shows the layout of experimental setup with instrumentation.

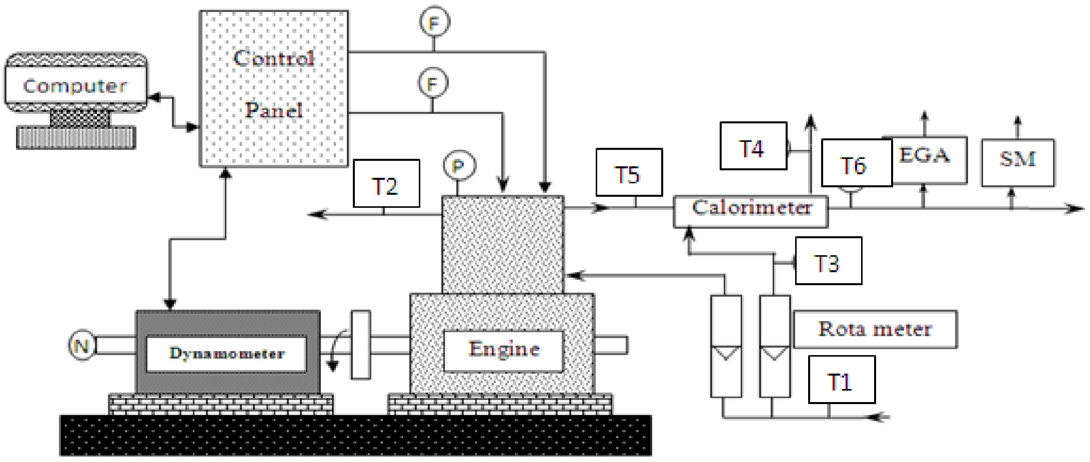


Figure 3.3 Block diagram of the VCR engine test rig

T1, T3	Inlet Water Temperature.
T2	Outlet Engine Jacket Water Temperature
T4	Outlet Calorimeter Water Temperature

T5	Exhaust Gas Temperature before Calorimeter
T6	Exhaust Gas Temperature after Calorimeter
F1	Fuel Flow DP (Differential Pressure) unit
F2	Air Intake DP unit
PT	Pressure Transducer
Wt	Load
N	RPM Decoder
EGA	Exhaust Gas Analyzer (5 gas).
SM	Smoke meter

3.3.2 Variable Compression Ratio engine Specifications

Table 3.3 Engine Specifications of the Variable Compression Ratio engine

Engine	Single cylinder 4 stroke Kirloskar Diesel engine Water cooled [Computerized].Modified to VCR Engine[CR:12-18],3.7kW,1500rpm
BORE AND STROKE	80 mm × 110 mm,
Dynamometer	Eddy current Water cooled
Air box	MS Fabricated with orifice meter and manometer
Fuel tank	15 Liter capacity with glass fuel metering column
Calorimeter	Type pipe in pipe
Piezo sensor	Range 5000 PSI, With low noise cable
Crank angle Sensor	Resolution 1 deg, Speed 5500RPM with TDC pulse
Temperature sensor	Type RTD, PT 100 and Thermocouple, Type K
Load indicator	Digital, Range 0-50kg, Supply 230 VAC
Load sensor	Load cell, type strain gauge, range 0-50 kg
Software	“EnginesoftLV” Engine performance analysis software
Rota meter	Engine cooling 40-400LPH; Calorimeter 25-250LPH
Overall dimensions	W 2000× D 2500 ×H 1500mm
Analysis	Through computer software

3.3.3 Experimental Procedure

Whole set of experiments were conducted at the designed injection timing of 27^{o}bTDC, speed of 1500RPM 18.5 and 17.5 compression ratios. The engine was started by hand cranking with diesel fuel supply, and it was allowed to get its steady state (for about 10minutes). Water to engine cooling jacket was maintained at about 350 liters/hour and water flow pressure to eddy current dynamometer was maintained between 1 to 1.5 bar throughout the experiments. This water flow pressure is maintained by means of 1/4th hp external water pump. The software was run and operated in ONLINE mode with a specific filename. To record the data online, software is logged every time and data stored in the computer hard disk, which can be retrieved as and when required.

The experiments were conducted at no-load, 25%, 50%, 75 % and 100% of full load conditions with neat diesel operation. Data such as fuel flow, air flow, exhaust temperature, exhaust smoke density, NOx, CO, CO_2, and HC emissions were recorded at these conditions.

3.3.4 Measurement system

The experimental set up was fully instrumented to measure the different parameters during the experiments on engine.

3.3.4.1 Flow Measurement

Air flow measurement was carried out by the flow sensors, a conventional U- tube manometer as well as air intake differential pressure transducers unit present in the control panel. There are two parallel air suction arrangements, one for U- tube manometer having a range of 100-0- 100 mm and another for pressure differential unit, which senses the difference in pressure between suction and atmospheric pressure. This difference in pressure will be sent to the transducer which will give the DC volt analog signal as output which in turn will be converted into digital signal by analog to digital converter and fed to the engine software.

For liquid fuel flow rate measurement, the fuel tank in the control panel was connected to the burette for manual measurement and to a fuel flow differential pressure unit for measurement through computer.

Cooling water flow to the engine and calorimeter is measured by means of a calibrated Rota meter with stainless steel float.

3.3.4.2Engine Speed Measurement

Engine speed is sensed and indicated by an inductive pick up sensor in conjunction with a digital RPM indicator, which is a part of the eddy current dynamometer-controlling unit. The dynamometer shaft rotating close to inductive pick up serves as an arrangement to send voltage pulse whose frequency is converted to RPM and displayed by digital indicator in the control panel, which is calibrated to indicate the speed directly in number of revolution per minute using rotary encoder.

3.3.4.3Load Measurement

The Eddy current dynamometer is provided to test the engine at different loading conditions. A strain gauge type load cell mounted beneath the dynamometer arm measures the load and signals are interfaced with ADC card to give load in kilogram. The dynamometer is loaded by the dynamometer-loading unit situated in the control panel.

3.3.4.4 Temperature Measurement

Temperature sensors of RADIX Pvt. Ltd. make are positioned at different locations to measure the following temperatures.

Inlet Water Temperature at Engine Jacket.	T1
Outlet Water Temperature at Engine Jacket	T2
Inlet Water Temperature at calorimeter.	T3
Outlet Water Temperature at calorimeter	T4
Exhaust Gas Temperature before Calorimeter	T5
Exhaust Gas Temperature after Calorimeter.	T6

All sensors, which sense the temperatures of respective locations, are connected to the control panel, which gives the digital reading of the respective temperatures.

3.3.4.5 Exhaust Gas Emission Measurement

A DELTA 1600-L of MRU make Exhaust gas analyzer is used to find the NOx (ppm), CO (%), UBHC (ppm), and CO_2 (%) emissions in the exhaust. The AVL437C smoke meter is used to measure the opacity of the exhaust gases. Opacity is the extinction of light between light sources and receiver. Opacity is measured in percentage.The Exhaust gas analyzer and smoke meter are shown in Figures 3.4and 3.5.

Figure 3.4 Exhaust analyzer

Figure 3.5 Smoke Meter

3.3.4 Calibration of instruments

All instruments were calibrated prior to their use in the tests. The suppliers calibrated the dynamometer and pressure sensors. The temperature sensors were calibrated with reference to standard thermometers. Rotomters were calibrated by manual measurement of the liquid flow rate through a known time.

3.4 EXPERIMENTATION WITH TWIN CYLINDER CI ENGINE TEST RIG

3.4.1 Experimental Procedure

In this work, the various performance and emission tests were conducted on four strokes twin cylinder engine manufactured by M/s Kirloskar (Block diagram of the engine is shown in fig 3.6) Company limited. The tests were conducted up to 25% blends, because the viscosity of above 25% blends exceeds the international standard limits (i.e. more than 5 Cst.).The parameter involved in performance analysis has been measured using the various equipments supplied by the engine manufacturer (Refer, specifications of the engine Table 3.3).The load test was conducted for different loads i.e. no load, 25%load, 50%load, 75%load and full load conditions.

A DELTA 1600-L of MRU make Exhaust gas analyzer was used to find the NOx (ppm), CO (%), UBHC (ppm), and CO_2 (%) emissions in the exhaust. The AVL437C smoke meter was used to measure the opacity of the exhaust gases. Opacity is the extinction of light between light sources and receiver and is measured in percentage.The Exhaust gas analyzer and smoke meter are shown in Figures 3.4and 3.5.

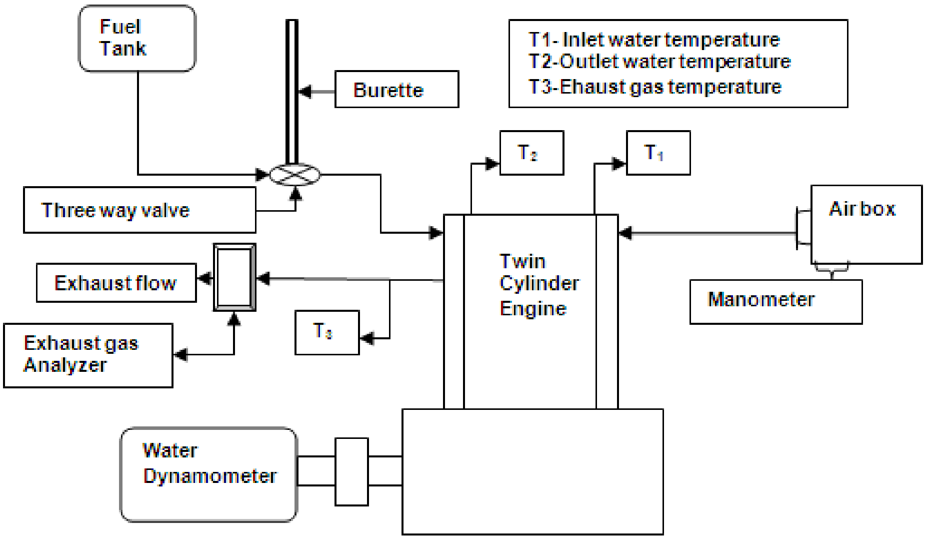


Figure 3.6 Twin cylinder engine test rig

3.4.2 Twin cylinder engine specifications

Table 3.4 Engine specifications of the twin cylinder engine

Engine specifications	
Engine type	Kirloskar, AV 2, Double Cylinder, Water cooled, and Four Stroke CI engine.
Rated power Output	10 HP
Speed	1500 RPM
Stroke length	110 mm
Bore Diameter	102 mm
Loading type	Hydraulic Dynamometer Load - Coupled to the engine through flexible coupling
Exhaust Gas Calorimeter	It consist of shell and pipe type vertical condenser with water inlet and outlet Connections and control valve.
Air Intake Measurement	It consists of air tank size 0.5 x 0.5 x 0.5m fitted with baffle orifice plate 0.02 m diameter. A'U' tube manometer to measure differential pressure.
Fuel Intake Measurement	Using fuel tank, 3 way cock and burette.
Temperature Measurement	Using thermocouple sensor with a multipoint digital temperature indicator for jacket water and exhaust calorimeter temperatures.

3.4.3Measurement of various parameters

- Water loading was manually done.
- Time for 10 cc of fuel consumption was measured using stop clock.
- Speed was measured by digital tachometer.
- Exhaust outlet was connected to exhaust gas analyzer and smoke meter.

3.4.3.1 Other measurements

Fuel consumption was volumetrically measured using metering burette; the consumption was determined by measuring the time for the consumption of a fixed fuel volume. The exhaust gas temperatures were recorded with chromel-alumel thermocouples. The engine was started on neat diesel fuel and warmed up. The warm up period ends when the cooling water temperature was stabilized.

3.5 PHOTOGRAPHS OF EXPERIMENTAL SET UP AND INSTRUMENTS

Figure 3.7 Photograph of Cardanol biodiesel before Experimentation

Figure 3.8Photograph of Single cylinder diesel engine

Figure 3.9Photograph of the exhaust gas analyzer probe at engine exhaust

Figure 3.10 Photograph of data collection in the computer

Figure 3.11 Photograph of VCR Diesel engine test rig

Figure 3.12 Isometric view of VCR engine

Figure 3.13 Photograph of Twin cylinder diesel engine test rig

CHAPTER-4

RESULTS AND DISCUSSIONS

4.1 General

The main objective was to study the performance and emission characteristics of the CI engines when Cardanol biodiesel and pure diesel volumetric blends were used and also to investigate which combination of fuel blend is suitable for diesel engine at all load conditions from both performance and emission point of view. Experimentation was conducted up to CBD volumetric blends 0, 10, 15, 20%, and 25%.

The experimental investigations have been carried out to evaluate the effect of different blends against the various PE characteristics in single and multi-cylinder engines. Section 4.4, covers the details of results and discussions of single cylinder diesel engine. Section 4.5, covers the details of results and discussions of VCR (variable compression ratio) engine. Finally, the chapter ends with Section 4.6, results and discussions of Kirloskar double cylinder CI engine.

4.2 TRANSESTERIFICATION PROCESSES

Selection of Raw Materials for transterification processes

Moisture free oil sample: Every time 2 liters of oil was taken in the reactor. To make it moisture free, the oil sample was heated to about 110ºC for one hour. Raising the oil temperature and cooling it back to room temperature has not varied the properties of oil.

Anhydrous methyl alcohol*:* 99% grade laboratory reagent type methyl alcohol, ethanol and iso-amyl alcohol was chosen.

Catalyst: Sodium hydroxide was selected for the purpose of catalyzing the reaction.

4.2.1Transterification Procedure

The following materials were used for the production of biodiesel. The cardanol oil and anhydrous methyl alcohol were used as reactants and sodium hydroxide was used as the catalyst. Researchers generally agree that NaoH catalyst reacts quickly during transesterification [7].For the production of biodiesel using transesterification, about 4 grams of NaOH (catalyst) was dissolved in 200 ml methanol to prepare alkoxide, which is required to activate the alcohol. Then stirring was done vigorously for twenty minutes in a covered container until the alkali is dissolved completely. Then the mixture is protected from atmosphere carbon dioxide and moisture as both destroy the catalyst. The alcohol catalyst (NaOH) mixture was then transferred to the reactor containing 700 ml moisture-free crude cardanol oil and stirring of the mixture was continued for 90 minutes at a temperature between 60-65 degree. The round bottom flask was connected to a reactor condenser and the mixture was heated for approximately three hours.

The mixture was distilling and condensing within the reactor condenser, with out glycerin, because CNSL was extracted from honeycomb structure (shell) of a cashew nut. The color of cardanol biodiesel slightly changed from dark brown to light brown and an average of 95% recovery of biodiesel was possible.

4.2.2Inference and observation after transterification:

- The mixture was distilling and condensing within the reactor condenser
- Viscosity reduced to half its normal value mainly due to dilution with methanol.
- No glycerin, because CNSL is extracted from honeycomb structure (husk or shell) of the cashew nut.

4.3 PROPERTY STUDY OF CARDANOL OIL

Vegetable oils (edible/non edible) typically have large molecules, with carbon, hydrogen and oxygen being present. Prior to the conduct of performance tests on the engine, the following important properties of cardanol oil, its blends with diesel fuel are determined.

The properties of the different blends were calculated by experiments, which were outsourced to a reputed testing lab outside [M/s Bangalore Test house Bangalore]. The comparisons of properties of these oils with conventional diesel are shown in Table 6.1.

4.3.1 Kinematic Viscosity

The viscosity is defined as the property of the fluid, which offers resistance to the flow of fluid over another adjacent layer. The kinematic viscosity of vegetable oils is in the range of 30-60 centistokes and biodiesel is in the range of 3-6 centistokes which is closer to diesel fuel (3-4centi stokes). The viscosity of these oils was found at various temperatures.

The weak Vander Waal's type forces between molecules provide cohesion to a body of fluid, and hence a resistance to internal displacement and flow. This resistance to flow is termed as viscosity. Liquid fuels expand when temperatures rise so that inter-molecular distances increase. Hence, the viscosity decreases.

4.3.2 Flash Point

The flashpoint of a fuel is the temperature at which the vapors above the fuel become flammable. Petroleum based diesel fuels have flash points of 50^0C to 80^0C & so they are considered to be intrinsically safe. Biodiesel has a flash point that is considerably higher than petroleum-based diesel fuel (above 160^0C). This means that the fire hazard associated with transportation, storage, and utilization of biodiesel is much less than with other commonly used fuels. The flash Point of oils is determined by using closed cup test method.

When thermal energy is added to the molecules of a 1iquid fuel, they escape from the free surface into the vapor-air mixture above. Consequently, the fuel concentration will reach a value sufficient enough to support combustion on the application of a flame or source of ignition. This fuel concentration represents the weak limit of its inflammability; the fuel temperature at which it occurs is the *weak temperature limit of flammability*, known as the *flash point*. Thus, the flash point is the lowest temperature of the fluid that allows inflammable vapors to be formed. A corresponding rich mixture limit of flammability, referred to as the *upper flash point* also exists but is not measured. The mixture is flammable at all points within the range of the mixture, or temperature, so defined.

4.3.3 Relative Density (or Specific Gravity)

The density of a liquid sample is defined as the mass of the sample occupying unit volume at the stated temperature of 15^oC.The relative density gives a broad indication of the type of fuel tested (for example, gasoline, diesel, or fuel oil). It gives the mass appropriate to a given storage volume. For fuels of a known type it serves as a general check for the presence of contaminants. It also influences the performance of pumps in the fuel systems and atomizers in the combustion chambers.

4.3.4 Calorific Value

Calorific value is defined in terms of the number of heat units liberated when unit mass of fuel is completely burnt in a calorimeter under specified conditions. The constant volume, gross (or higher) calorific value (or heating value) of a liquid fuel is determined, as in the case of solid fuels, in a bomb calorimeter.

The following table 4.1 depicts the various properties of diesel and cardanol biofuel volumetric blends.

Table 4.1 Properties of Cardanol bio fuel blends

Properties	**Diesel**	**B10**	**B15**	**B20**	**B25**	**B30**
Flash point (°C)	50	53	55	56	58	61
Density(kg/m^3)	817	823	829	836	841	846
Viscosity(mm^2/sec) at 40 degree C	2.00	2.50	3.10	3.50	4.20	5.50
Calorific value (kJ/kg)	40000	40130	40196	40261	40326	40392

From the properties studies, properties like density, viscosity, flash and fire points of cardanol biodiesel volumetric blends under test are higher, and calorific values are lower and are in the range of 94-96%that of diesel.

4.4 PERFORMANCE AND EMISSION CHARACTERISTICS OF SINGLE CYLINDER AT DIFFERENT LOAD CONDITIONS

The performance and emission studies were carried out on a single cylinder naturally aspirated direct injection diesel engine by cardanol biofuel blends of 0%, 10%, 15%, 20% and 25% volumetric blends. The same parameters were repeated three times, on the same engine in order to achieve best results.

4.4.1 Results and discussions

The experiments were conducted on a direct injection compression ignition engine for various loads with an intention of studying the behavior of the engine in regard to various emissions and performance characteristics when it was run on different blends and the results of the performance test are as fallows.

4.4.2 Brake Specific Energy Consumption

Figure 4.4.1 depicts that the brake specific energy consumption decreases by 30 to 40% approximately with increase in load conditions. This reverse trend was observed due to lower calorific value and higher viscosity with increase in biofuel percentage in the blends.

4.4.3 Brake Thermal Efficiency

The variation of brake thermal efficiency with load for different volumetric blends is presented in figure 4.4.2. In all cases, it increased with increase in load. This was due to reduction in heat losses and increase in brake power with increase in load. The brake thermal efficiency obtained for B25 was less than that of diesel. This lower brake thermal efficiency obtained could be due to lower calorific value and increase in fuel consumption as compared to diesel.

4.4.4 Exhaust gas temperature

The variations of Exhaust gas temperature with respect to Brake Power with different engine loading are presented in figure 4.4.3. The exhaust gas temperature increased linearly form 180^{o} C at no load to $480\ ^{o}$ C at full load conditions. This increasing trend of EGT is mainly because of generating more power and consumption of more fuel at higher loads.

4.4.5 Nitrogen oxides Emissions

From the figure 4.4.4, it is observed that NOx emissions (ppm) increase with increased proportion of blends and also with higher EGT. NO_x emissions are sensitive to the spry characteristics, temperature and oxygen. The spry characteristics of a fuel depend on droplet size, penetration rate, evaporation rate, degree of mixing with the air etc. A change in any of these properties may change NO_x production.

This trend is mainly because of presence of oxygen in biofuel, and leads to more oxidation at higher temperature and also is responsible for more No_x emissions.

4.4.6 Hydrocarbon Emissions

From the figure 4.4.5, it is observed that HC emissions are nominal up to B20, and more at B25, the reasons for this being the incomplete combustion and physical properties of the CBD.

4.4.7 Carbon monoxide Emissions

From figure 4.4.6, it is observed that the carbon monoxide emissions increased with higher blends, and increased slightly more after 20% blends. The minimum and maximum CO produced was 0.03-0.06%. At higher loads CO emissions slightly decrease. At elevated temperature, performance of the engine improved with relatively better burning of the fuel resulting in decreased CO.

4.4.8 CLOSER

- From the results, the brake specific energy consumption decreases by 30 to 40% approximately with increase in load conditions.
- Brake thermal efficiency, increased with increase in load. This was due to reduction in heat losses and increase in brake power with increase in load. The exhaust gas temperature increased linearly form 18^{o} C at no load to 48^{o} C at full load conditions. This increasing trend of EGT is mainly because of generating more power and consumption of more fuel at higher loads.
- From the results, it is observed that NOx emissions (ppm) increased with increased proportion of blends and also with higher EGT. This trend is mainly because of presence of oxygen in the biofuel. This leads to more oxidation at higher temperature and is responsible for more No_x emissions.
- From the results, it is observed that HC emissions are nominal up to B20, and more at B25. The reason for this is the incomplete combustion and physical properties of the CBF.

- From the results, it is observed that the carbon monoxide emission increased with higher blends, and increased slightly more after 20% blends. The minimum and maximum CO produced was 0.03-0.08%.

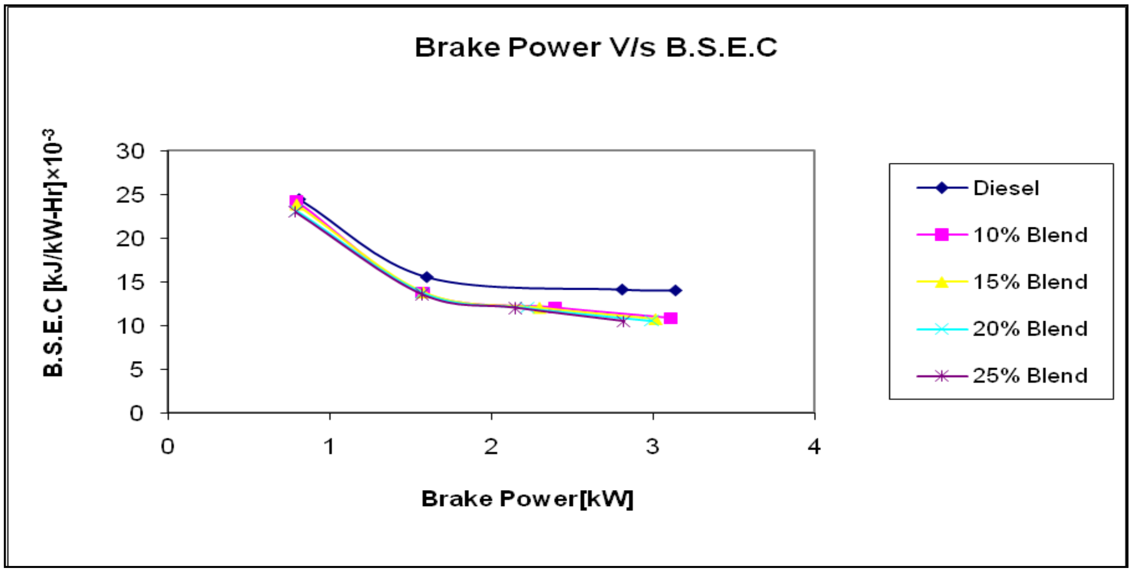


Figure 4.4.1 Variations of Brake Specific Energy Consumption against the Brake Power for different Cardanol Biofuel blends.

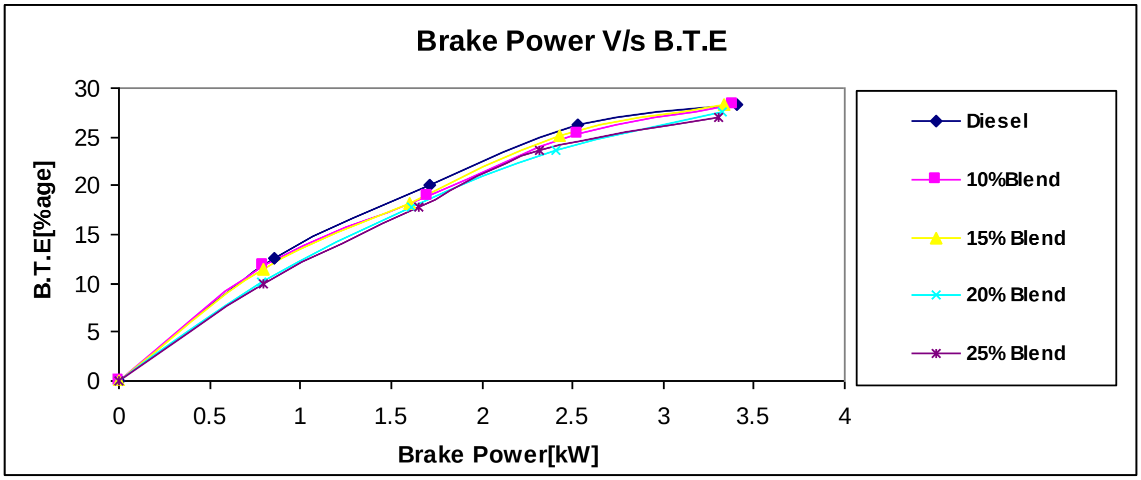


Figure 4.4.2 Variations of Brake Thermal Efficiency against the Brake Power for different Cardanol Biofuel blends

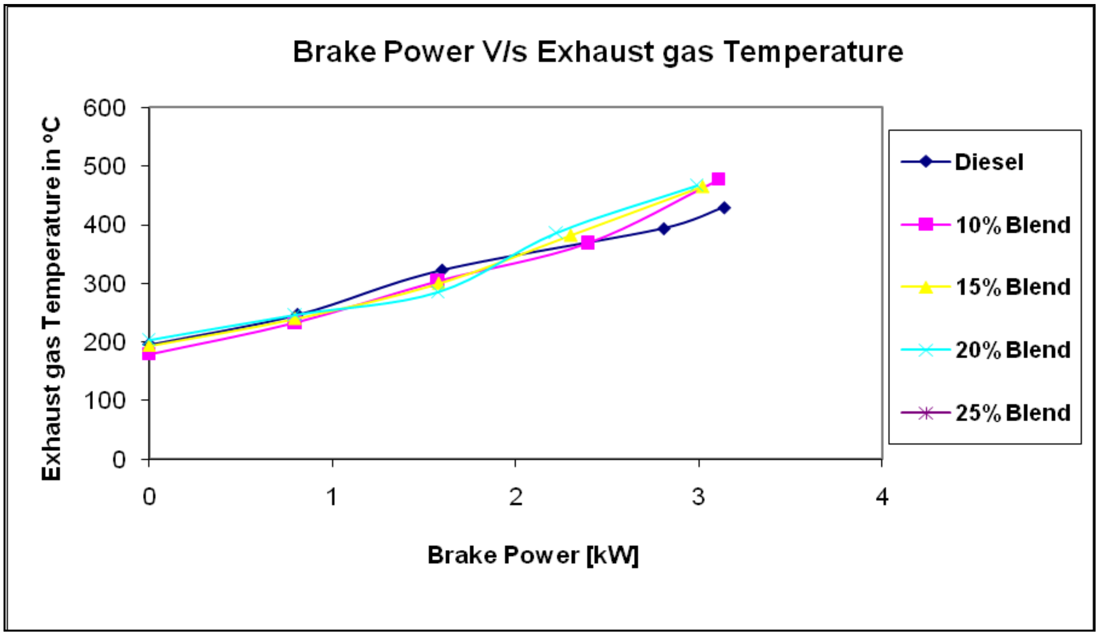


Figure 4.4.3 Variations of Exhaust gas temperature against the Brake Power for different Cardanol Biofuel blends

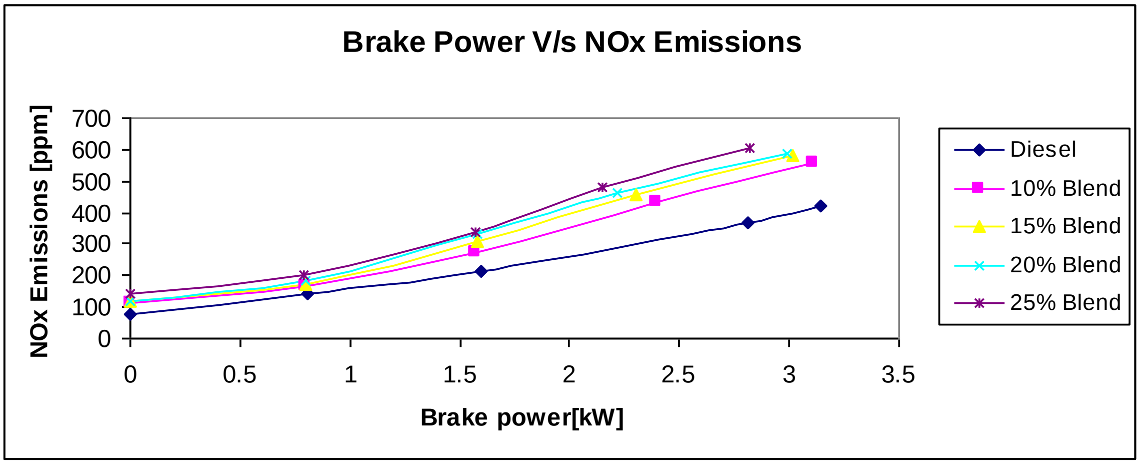


Figure 4.4.4 Variations of NOx Emissions against the Brake Power for different Cardanol Biofuel blends.

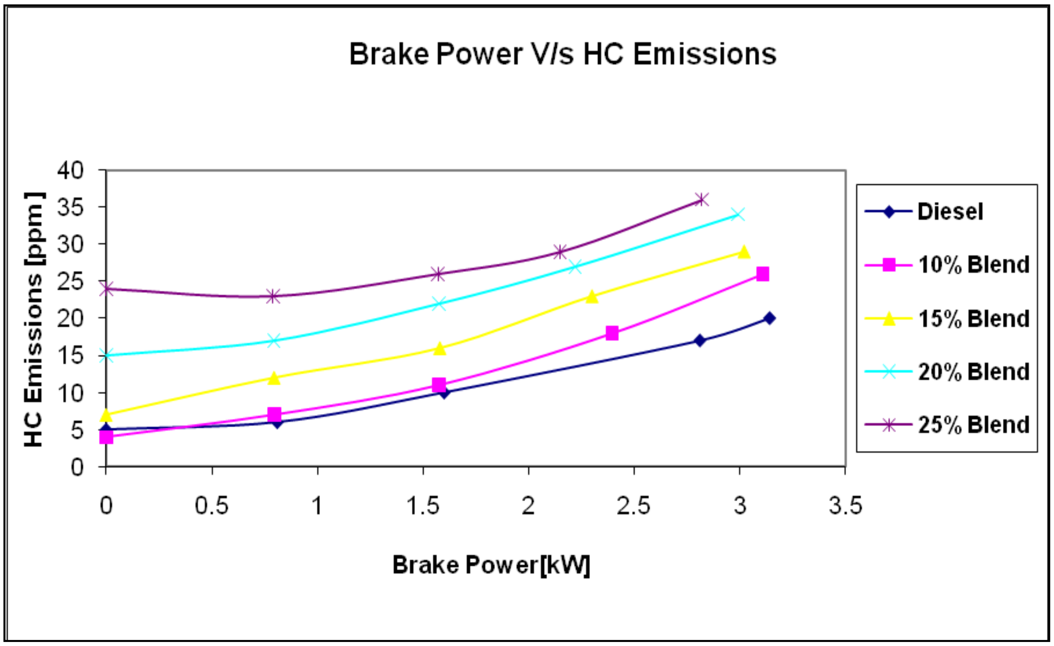


Figure 4.4.5 Variations of H C Emissions against the Brake Power for different Cardanol Biofuel blends

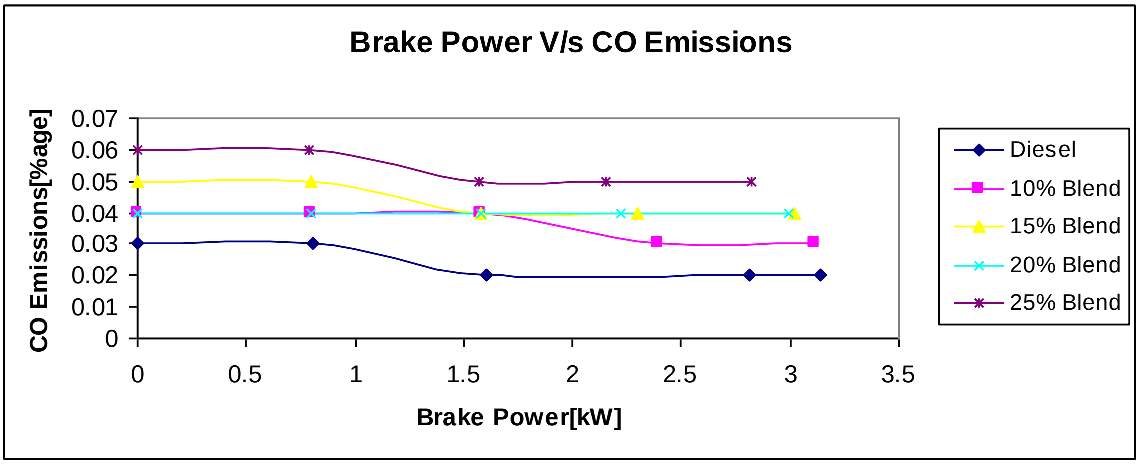


Figure 4.4.6 Variations of CO Emissions against the Brake Power for different Cardanol Biofuel blends.

4.5 PERFORMANCE AND EMISSION CHARACTERISTICS OF SINGLE CYLINDER VCR-CI ENGINE AT DIFFERENT LOAD CONDITIONS

The performance and emission studies have been carried out on a single cylinder naturally aspirated direct injection diesel engine by cardanol biofuel blends of 0%, 10%, 15%, 20% and 25% volumetric blends. The same parameter has been repeated for three times, on the same engine in order to achieve best results.

The experiments has been conducted on a direct injection compression ignition engine for various loads with an intention of studying the behavior of the engine concerning various emissions, and performance characteristics when it was run on different blends. The various PE results has been compared and plotted against the brake power at 18:1 and 17:1compression ratios. The results of the performance test are as fallows.

4.5.1 Brake Thermal Efficiency

The variation of brake thermal efficiency with load for different volumetric blends is presented in figure 4.5.1 and 4.5.7. In all cases, it increased with increase in load. This was due to reduction in heat losses and increase in brake power with increase in load. The brake thermal efficiency obtained for B25 was less than that of diesel i.e. 2 to 3 % at 18:1 CR and 5 to 6 % at 17:1 CR. This lower brake thermal efficiency obtained could be due to lower calorific value and increase in fuel consumption as compared to diesel.

4.5.2 Brake Specific Energy Consumption

Figure 4.5.2 and 4.5.8 depict that, the Brake Specific Energy Consumption with Brake Power for cardanol biofuel blends. B.S.E.C decrease by 15 to 22% approximately with increase in load conditions. This reverse trend was observed due to lower calorific value with increase in biofuel percentages in the blends. The main reason for this could be the percentage increase in fuel required to operate the engine is less than the percent increase in the brake power due to relatively less portion of the heat loss at higher loads.

The BSEC for B20 was observed to be lower than diesel. In case of B15 & B25 it was slightly less compared that of neat diesel. This reverse trend was observed due to lower calorific value with increase in biofuel percentages in the blends.

4.5.3 Exhaust gas temperature

The variations of exhaust gas temperature with respect to brake power for different engine loading are presented in the in figures 4.5.3 & 4.5.9 The exhaust gas temperature increases linearly form 180^{o} C at no load to 480 ^{o} C at full load conditions in both compression ratios, but slightly lower exhaust gas temperature is noticed in the case of 17:1 CR. This increasing trend of EGT is mainly because of generating more power and consumption of more fuel at higher loads.

4.5.4 Nitrogen oxides Emissions

The NOx values as parts per million (ppm) for different CBD blends of emissions VCR engine are plotted as a function of load in figures 4.5.5 & 4.5.11. It is observed that NOx emissions (ppm) increase with increased proportion of blends and also with higher EGT. This trend is mainly because of presence of oxygen in the biofuel. This leads to more oxidation at higher temperature and is responsible for more NO_x emissions. The NO_x emissions at 17:1 Compression ratio slightly lower than that of 18:1 CR. This is mainly because of lower exhaust gas temperature in the case of 17:1CR.

4.5.5 Hydrocarbon Emissions

The figures 4.5.4 and 4.5.10 depict the variation of HC emissions with different load conditions. From the figures it is observed that HC emissions are nominal up to B20, and slightly more at B25. The reason for this is the incomplete combustion.

4.5.6 Carbon monoxide Emissions

From figures 4.5.6 and 4.5.12, it is observed that the carbon monoxide emissions increase with higher blends, and increase slightly more after 20% blends. The minimum and maximum CO produced was 0.03-0.08%. At higher loads, except 25 % blend CO emissions slightly decreased. At elevated temperature, performance of the engine improved with relatively better burning of the fuel resulting in decreased CO.

4.5.7 Closer

The CNSL and its extracts showed promising results in terms of engine performance in par with conventional CI engine fuels. Based on the results of the study the following conclusions were drawn.

- ✓ The brake specific energy consumption decreased by 30 to 40% approximately at higher CR and 25 to 30% at lower CR with increased in brake power. This reverse trend was observed to be due to lower calorific value with increase in bio fuel percentage in the blends.

- ✓ The brake thermal efficiency increased with higher BP. In all cases (both in CR18 and CR17), it increased with increase in BP. This was due to reduction in heat losses and increase in brake power with increase in load. The brake thermal efficiency obtained for cardanol biofuel volumetric blends was less than that of diesel.

- ✓ The increasing trend of EGT was mainly because of generating more power and consumption of more fuel at higher loads. Smoke density was nominal up to B20 and more at B25. The reason for this is the incomplete combustion.

- ✓ The NOx values as parts per million (ppm) for different CBF blends increased with increased proportion of blends and also with higher EGT. This trend was mainly because of presence of oxygen in the biofuel. This leads to more oxidation at higher temperature and responsible for more Nox emissions. The NOx emissions at 17:1 compression ratio were slightly lower than that of 18:1 CR. This mainly because of lower exhaust gas temperature in the case of 17:1CR.

- ✓ From the results it is observed that HC emissions are nominal up to B20, and slightly more at B25. The reason for this is the incomplete combustion.

- ✓ From the results, it is observed that the carbon monoxide emissions increased with higher blends, and increased slightly more after 20% blends. The minimum and maximum CO produced was 0.03-0.08%. At higher loads, except 25 % blend

CO emissions slightly decreased. At elevated temperature, performance of the engine improved with relatively better burning of the fuel resulting in decreased CO.

4.5.1.8 Various graphs of VCR engine at 18:1 compression ratio

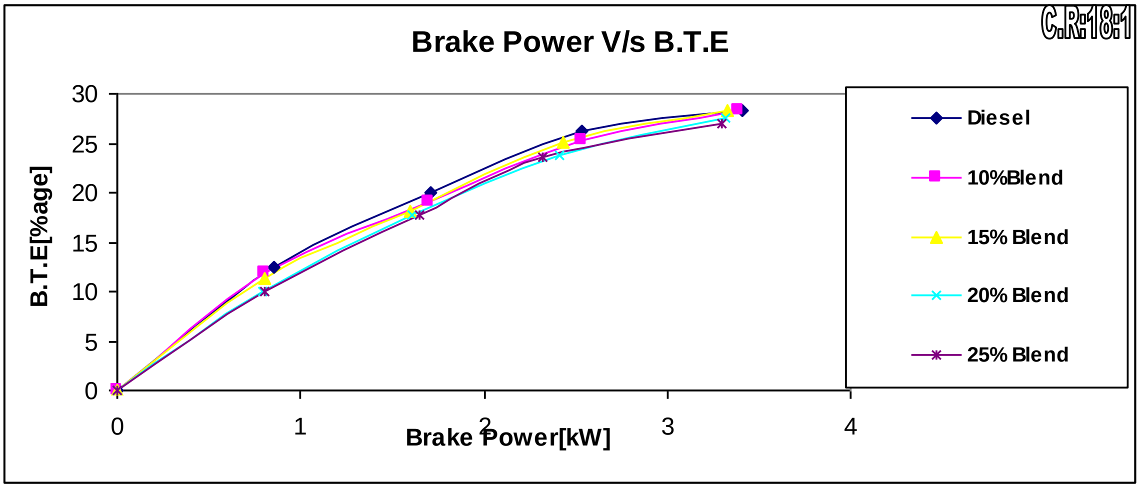


Figure 4.5.1 Comparison of Brake Thermal Efficiency against the Brake Power for Cardanol Biofuel blends.

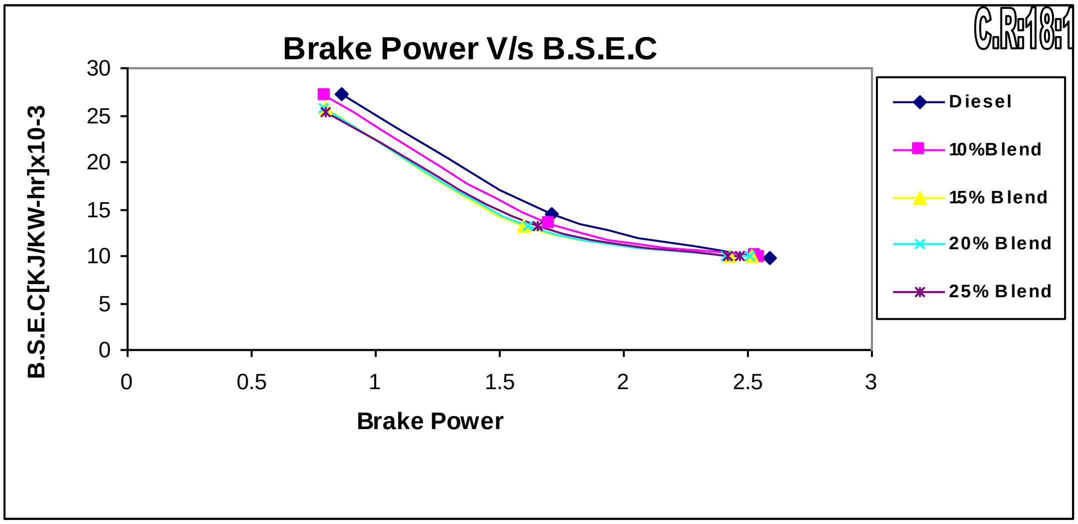


Figure 4.5.2 Comparison of Brake Specific Energy Consumption against the Brake Power for Cardanol Biofuel blends.

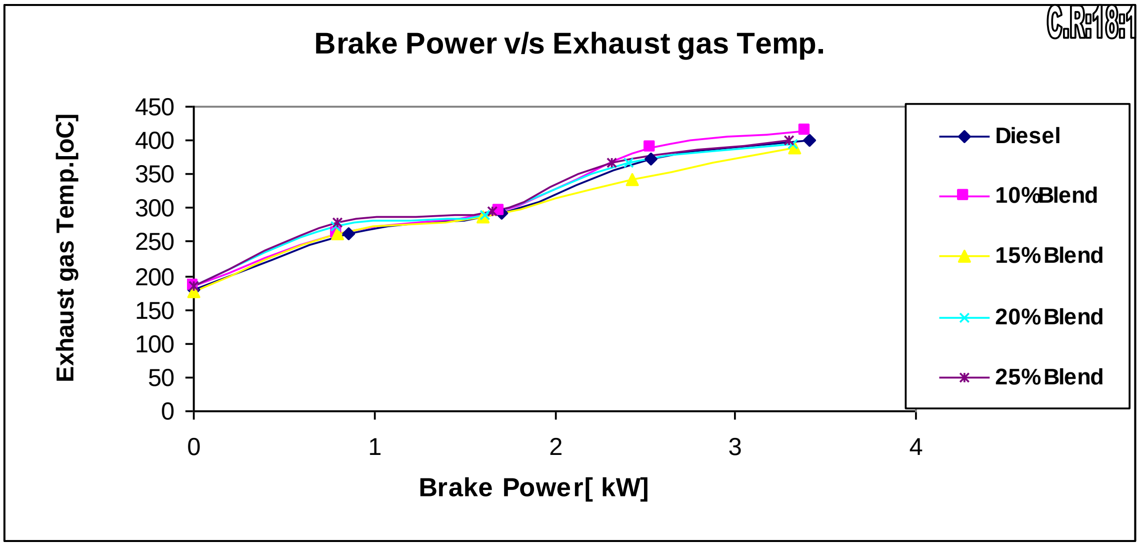


Figure 4.5.3 Comparison of Exhaust gas temperature against the Brake Power for Cardanol Biofuel blends.

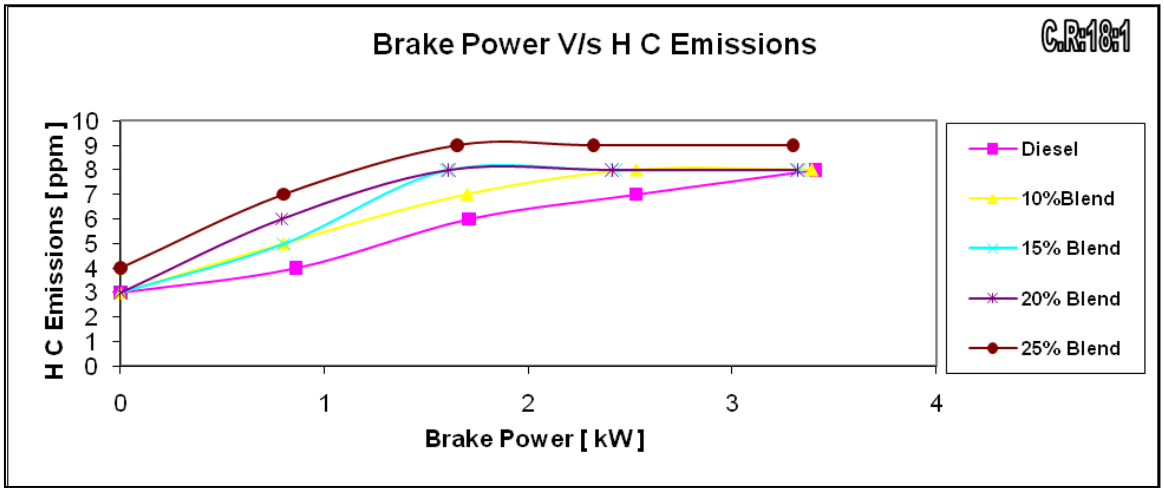


Figure 4.5.4 Comparisons of H C Emissions against the Brake Power for Cardanol Biofuel blends.

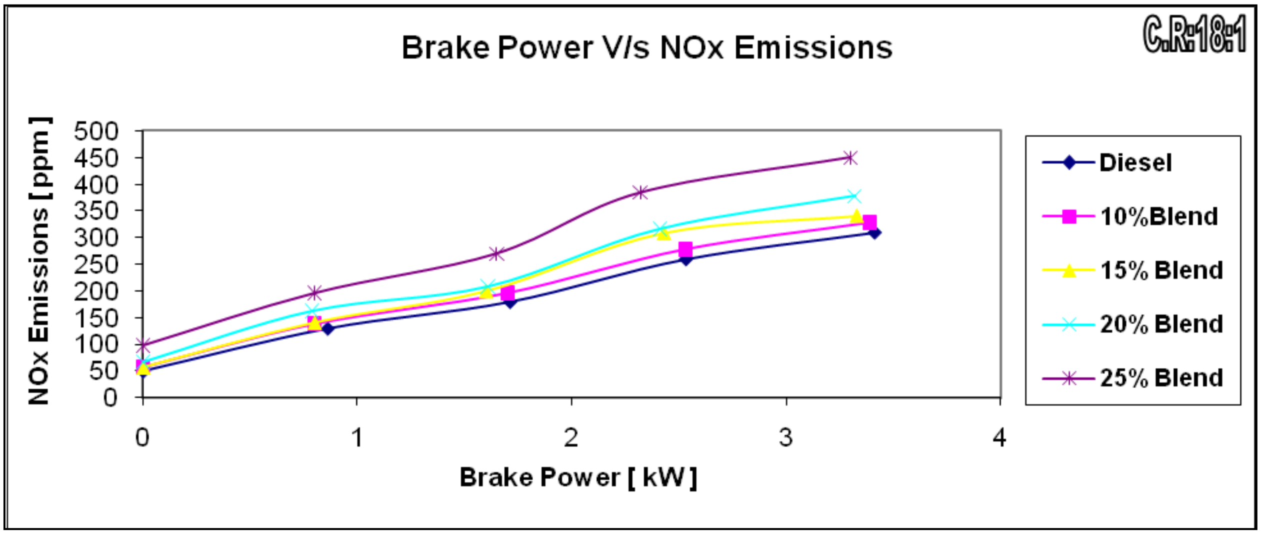


Figure 4.5.5 Comparisons of NOx Emissions against the Brake Power for Cardanol Biofuel blends.

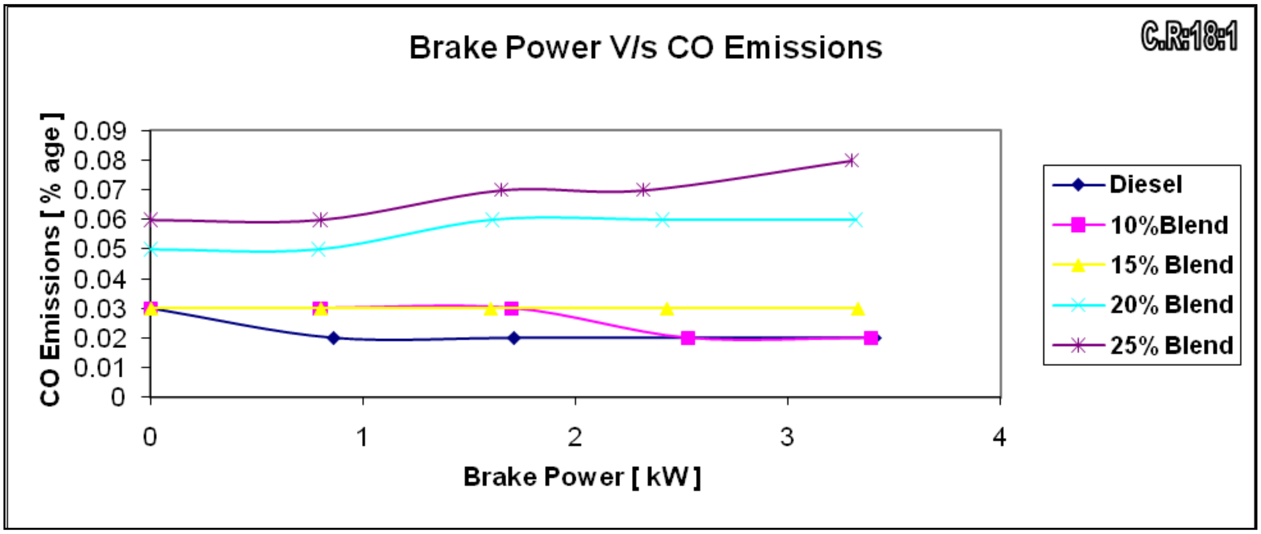


Figure 4.5.6 Comparisons of CO Emissions against the Brake Power for Cardanol Biofuel blends.

7.4.8 Various graphs of VCR engine at 17:1 compression ratio

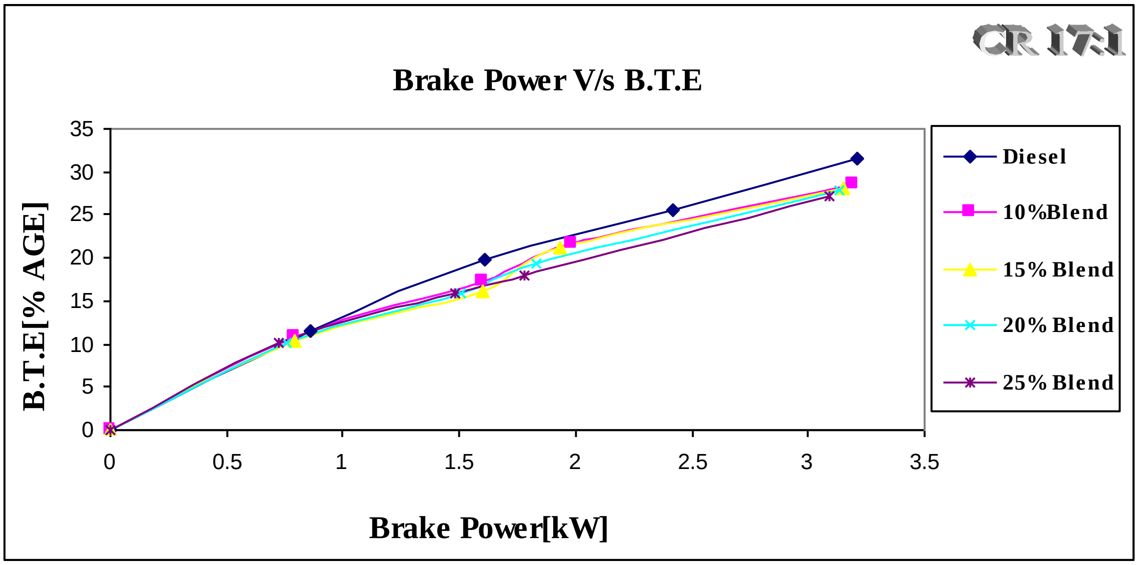


Figure 4.5.7 Comparison of Brake Thermal Efficiency against the Brake Power for Cardanol Biofuel blends.

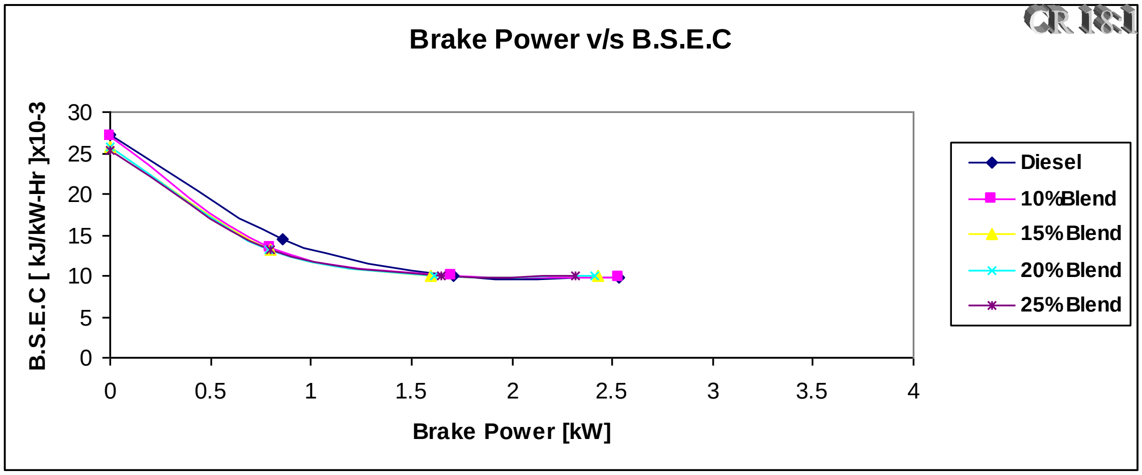


Figure 4.5.8 Comparison of Brake Specific Energy Consumption against the Brake Power for Cardanol Biofuel blends.

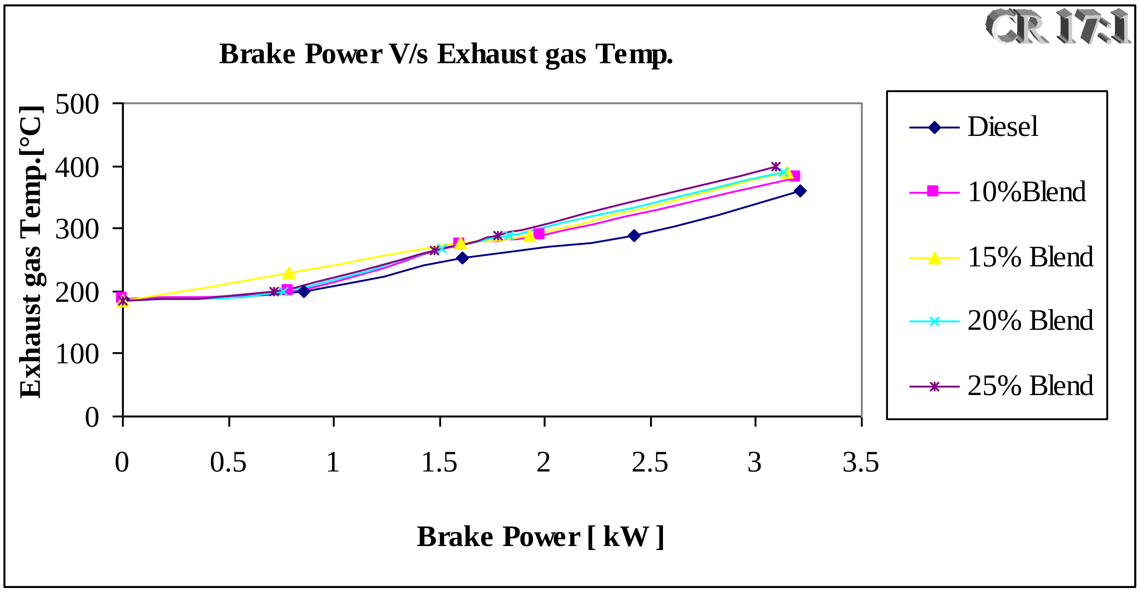


Figure 4.5.9 Comparison of Exhaust gas temperature against the Brake Power for Cardanol Biofuel blends.

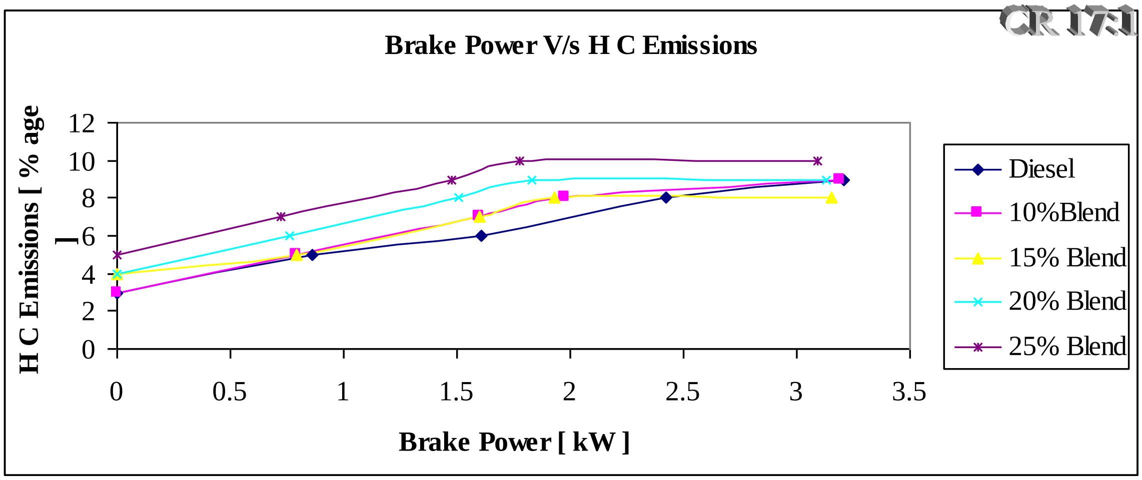


Figure 4.5.10 Comparisons of H C Emissions against the Brake Power for Cardanol Biofuel blends.

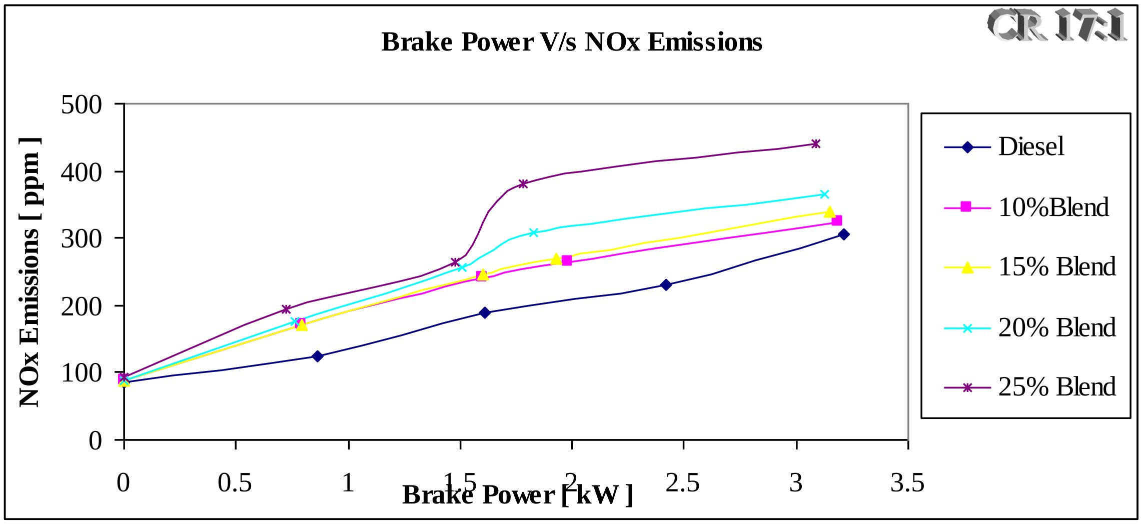


Figure 4.5.11 Comparisons of NOx Emissions against the Brake Power for Cardanol Biofuel blends.

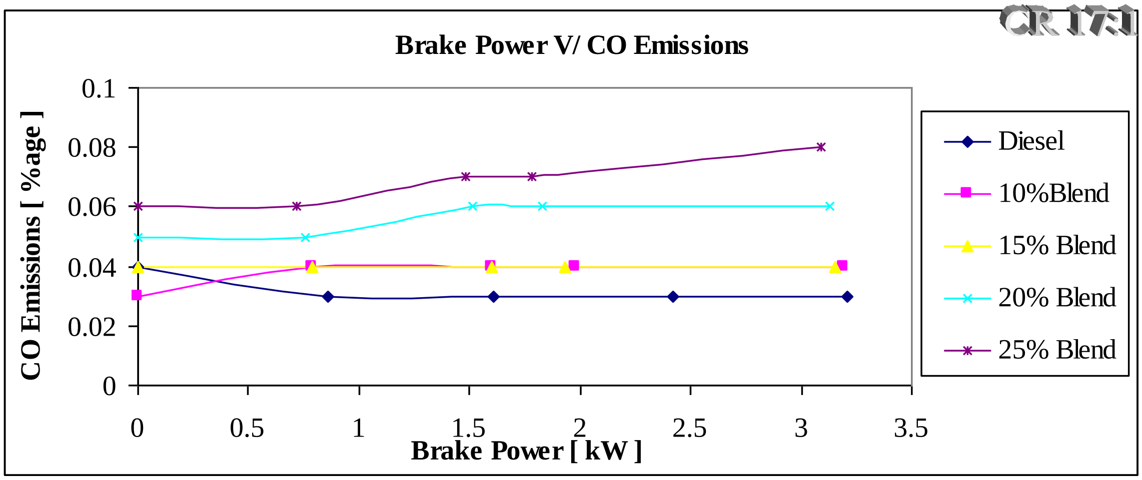


Figure 4.5.12 Comparisons of CO Emissions against the Brake Power for Cardanol Biofuel blends.

4.6. PERFORMANCE AND EMISSION CHARACTERISTICS OF TWIN CYLINDER CI ENGINE AT DIFFERENT LOAD CONDITIONS

The experiments have been conducted on a direct injection double cylinder compression ignition engine by cardanol biodiesel blends of 0%, 10%, 15%, 20% and 25% volumetric blends. The same parameters were repeated three times, on the same engine in order to achieve best results.

Tests were conducted for various loads with the intention of studying the behavior of the engine concerning various emissions, and performance characteristics. After the engine was run on different volumetric blends, the results of the performance test are as fallows.

4.6.1 Brake Thermal Efficiency

The variation of brake thermal efficiency with brake power for different volumetric blends is presented in figure 4.6.1. In all cases, it increased with increase in brake power. This was due to reduction in heat losses and increase in brake power with increase in load. The brake thermal efficiency obtained for CBD blends was less than that of diesel. This lower brake thermal efficiency obtained could be due to lower calorific value and increase in fuel consumption as compared to diesel.

4.6.2 Brake Specific Energy Consumption

Figure 4.6.2, shows that, the brake specific energy consumption decreases by 15 to 20% approximately with increases in brake power. This reverse decreasing trend observed may be due to lower calorific value with increase in biodiesel percentage in the blends.

4.6.3 Exhaust gas temperature

The variations of exhaust gas temperature with brake power for different engine loading, are presented in figure 4.6.3. The exhaust gas temperature increases linearly form 180^{o} C at no load to 480 ^{o} C at full load conditions. This increasing trend of EGT is mainly because of generating more power and consumption of more fuel at higher loads.

4.6.4 Nitrogen oxides Emissions

The variations of NO_x emissions with respect to brake power are presented in figure 4.6.5. From the figure, it is observed that NOx emissions (ppm) increased with increased proportion of blends and also with higher EGT (This increasing trend of EGT is mainly because of generating more power and consumption of more fuel at higher loads). This trend is mainly because of presence of oxygen in biodiesel, which leads to more oxidation at higher temperature and is responsible for more No_x emissions.

4.6.5 Hydrocarbon Emissions

From the figure 4.6.4, it is observed that HC emissions are nominal up to B20, and more at B25 and the reason for this may be due to incomplete combustion.

4.6.6 Carbon monoxide Emissions

From figure 4.6.6, it is observed that the carbon monoxide emissions increase with higher blends, and increase slightly more after 20% blends. The minimum and maximum CO produced was 0.03-0.08%. At higher loads CO emissions slightly decreased. At elevated temperatures, performance of the engine improved with relatively better burning of the fuel resulting in decreased CO.

4.6.7 Smoke Absorptivity & Opacity

The variations of smoke absorptivity & opaci**ty** with respect to brake power are presented in figures 4.6.7 and 4.6.8. There is a reduction in smoke density for CBD volumetric blends at higher brake power. This trend is mainly due to the presence of internal availability of oxygen content in the CBD and neat burning of fuel at elevated temperatures (As the oxygen content in the fuel increases, smoke content in the exhaust is reduced).

4.6.8 SUMMARY

Based on the results of the study the following conclusions were drawn.

- The brake specific energy consumption decreased by 30 to 40% approximately with increase in brake power. This reverse trend was observed due to lower calorific value with increase in biofuel percentage in the blends.

- The brake thermal efficiency increase with higher loads. In all cases, it increase with increase in load. This was due to reduction in heat losses and increase in brake power with increase in load. The brake thermal efficiency obtained for cardanol biodiesel volumetric blends was less than that of diesel. This lower brake thermal efficiency obtained could be due to lower calorific value and increase in fuel consumption as compared to diesel.
- The NO_x emissions (ppm) increased with increased proportion of blends and also with higher EGT. This trend is mainly because of presence oxygen in biodiesel, this leads to more oxidation at higher temperature and responsible for more NO_x emissions.
- The HC emissions are nominal up to B20, and more at B25, the reason for this being the incomplete combustion.
- The Carbon monoxide emissions increased with higher blends, and increased slightly more after 20% blends. At higher loads CO emissions slightly decreased, which may be due to the fact that at higher temperatures the performance of the engine improved with relatively better burning of the fuel resulting in decreased CO.
- From this investigation it is observed that up to 20% blends of cardanol biodiesel may be used in CI engines without any modifications.

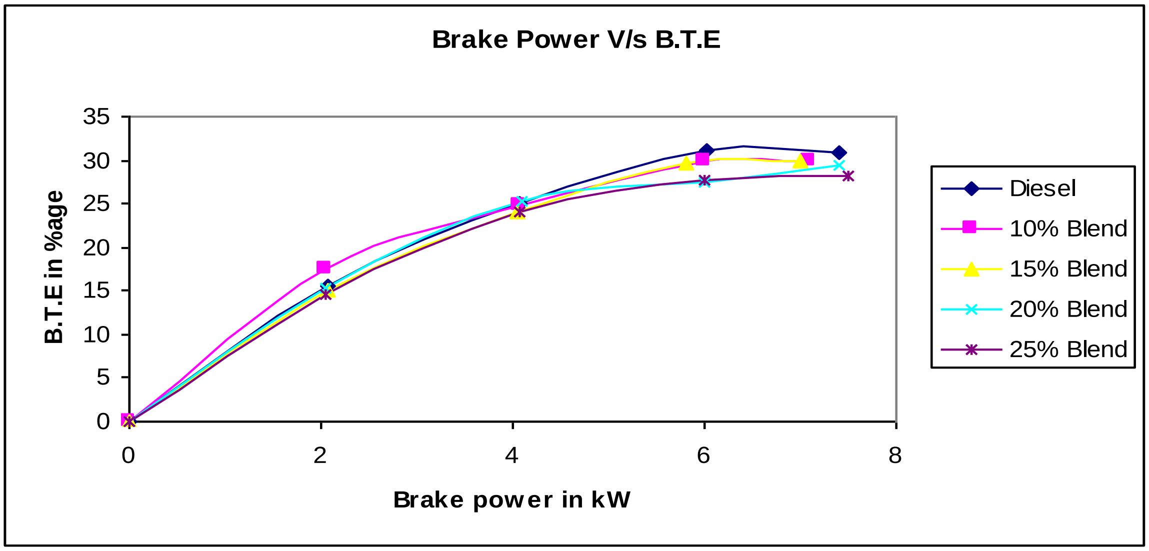


Figure 4.6.1 Variations of Brake Thermal Efficiency against the Brake Power for different Cardanol biodiesel **blends.**

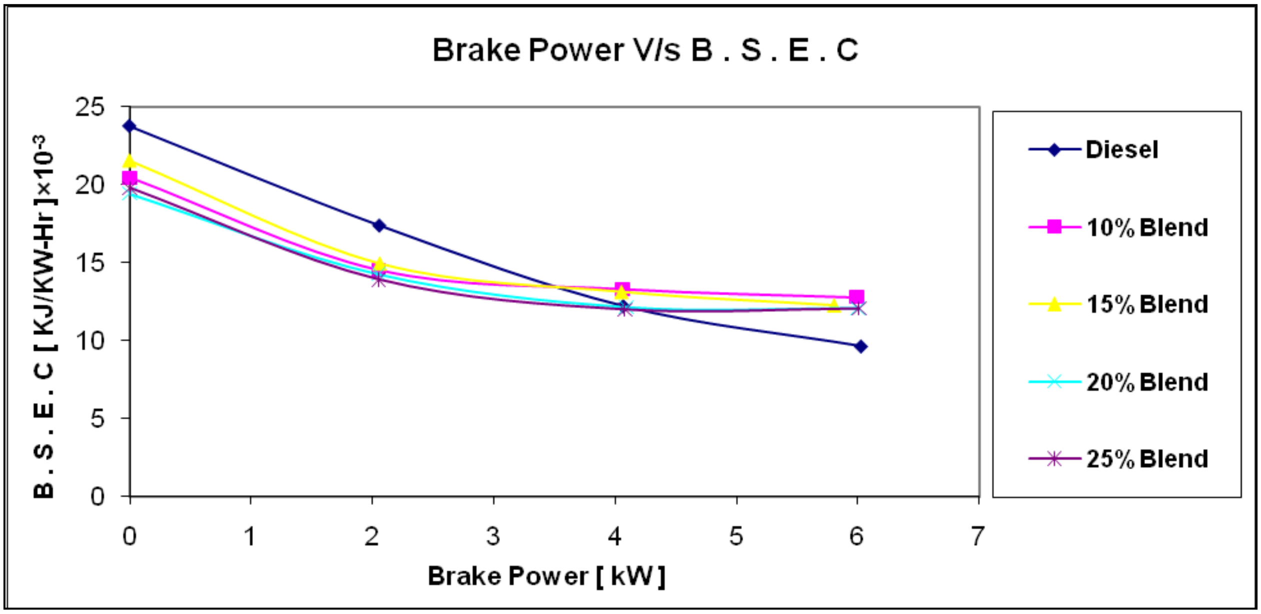


Figure 4.6.2 Variations of Brake Specific Energy Consumption against the Brake Power for different Cardanol biodiesel blends.

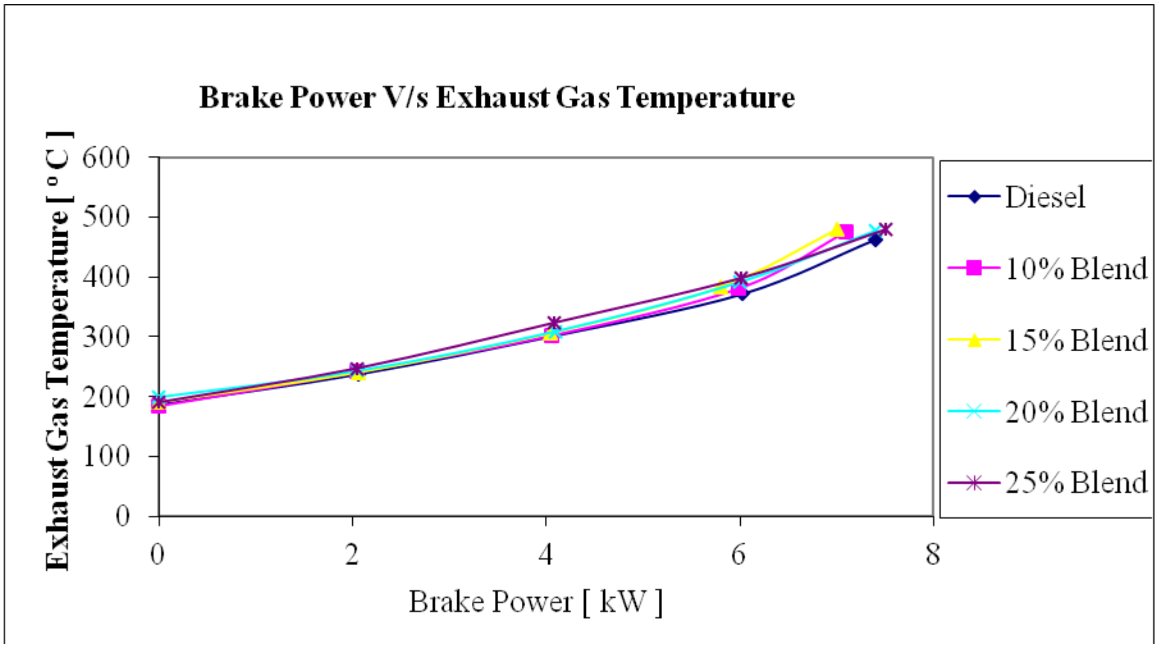


Figure 4.6.3 Variations of Exhaust gas temperature against the Brake Power for different Cardanol biodiesel blends.

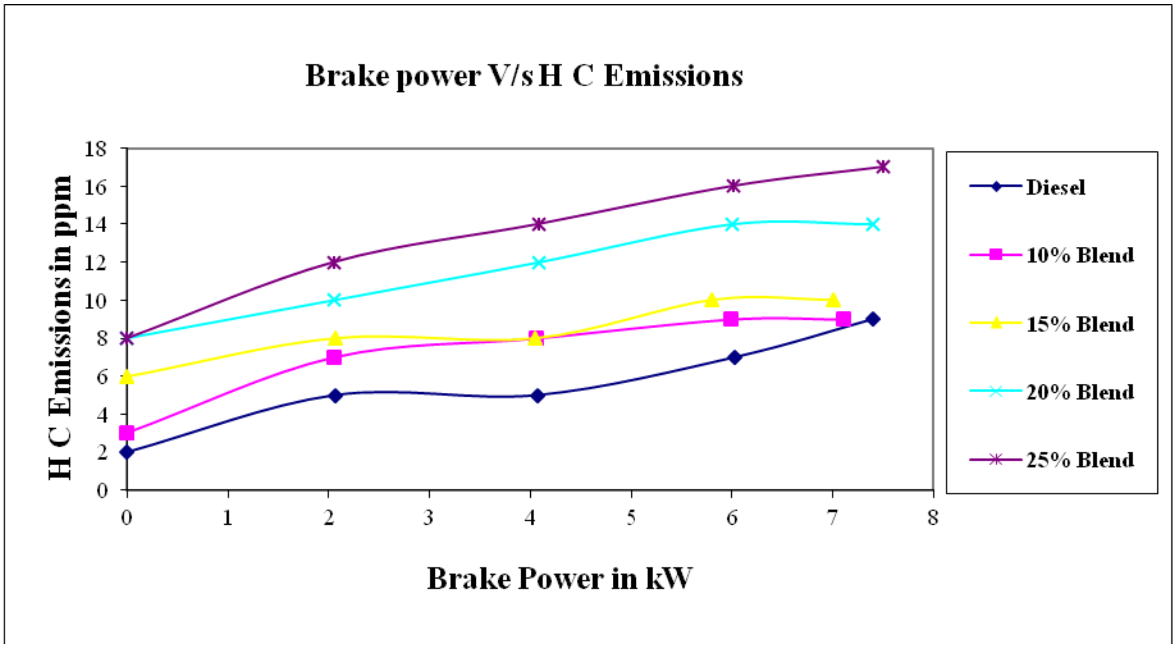


Figure 4.6.4 Variations of HC Emissions against the Brake Power for different Cardanol biodiesel **blends.**

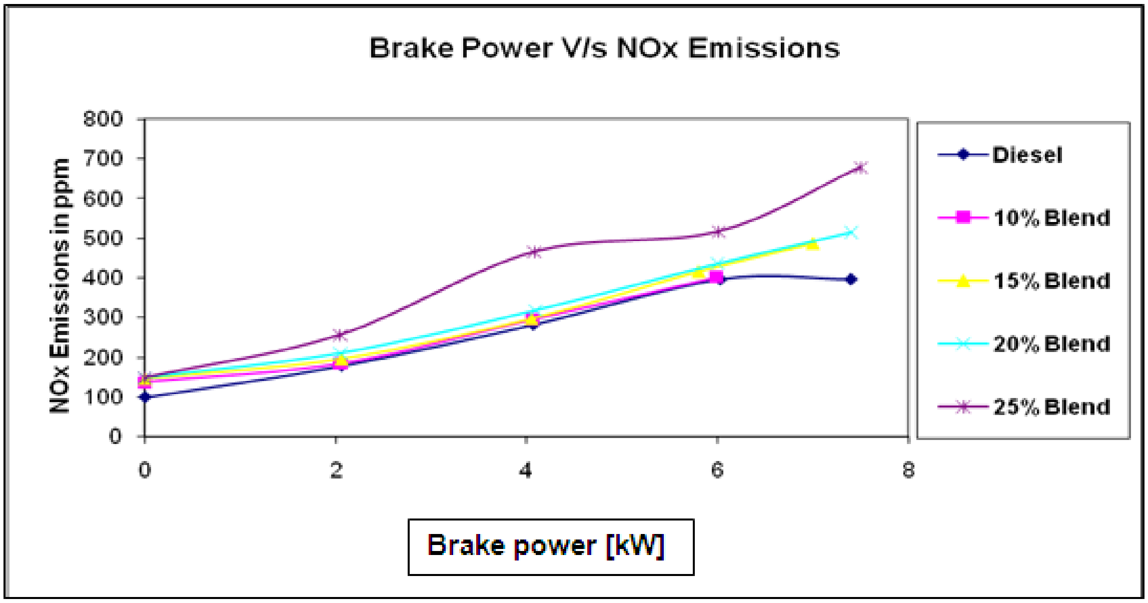


Figure 4.6.5 Variations of NOx Emissions against the Brake Power for different Cardanol biodiesel **blends.**

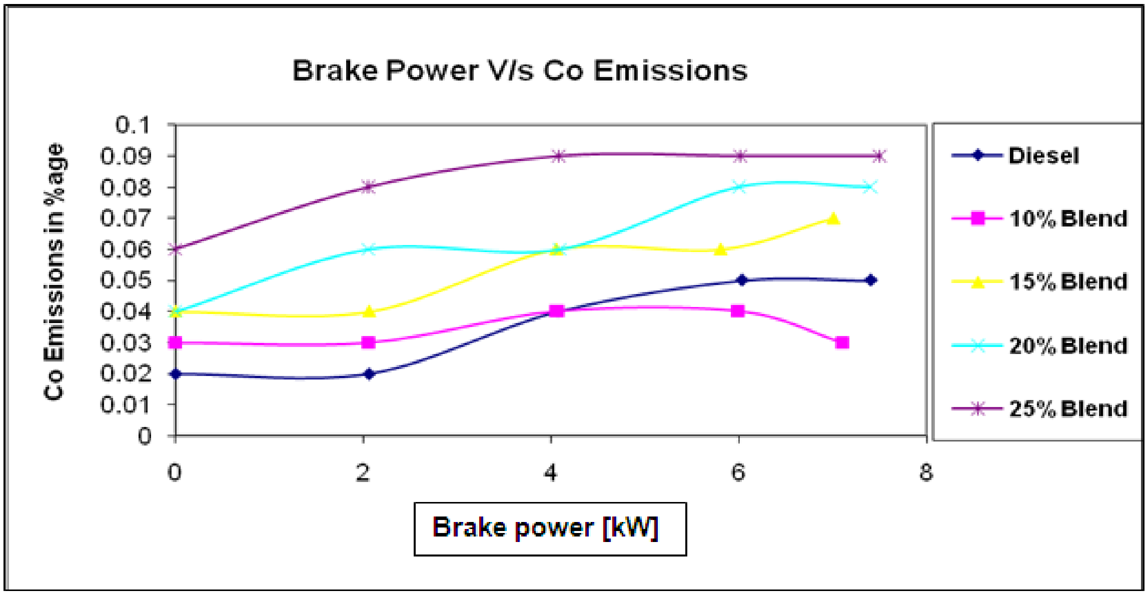


Figure 4.6.6 Variations of CO Emissions against the Brake Power for different Cardanol biodiesel **blends.**

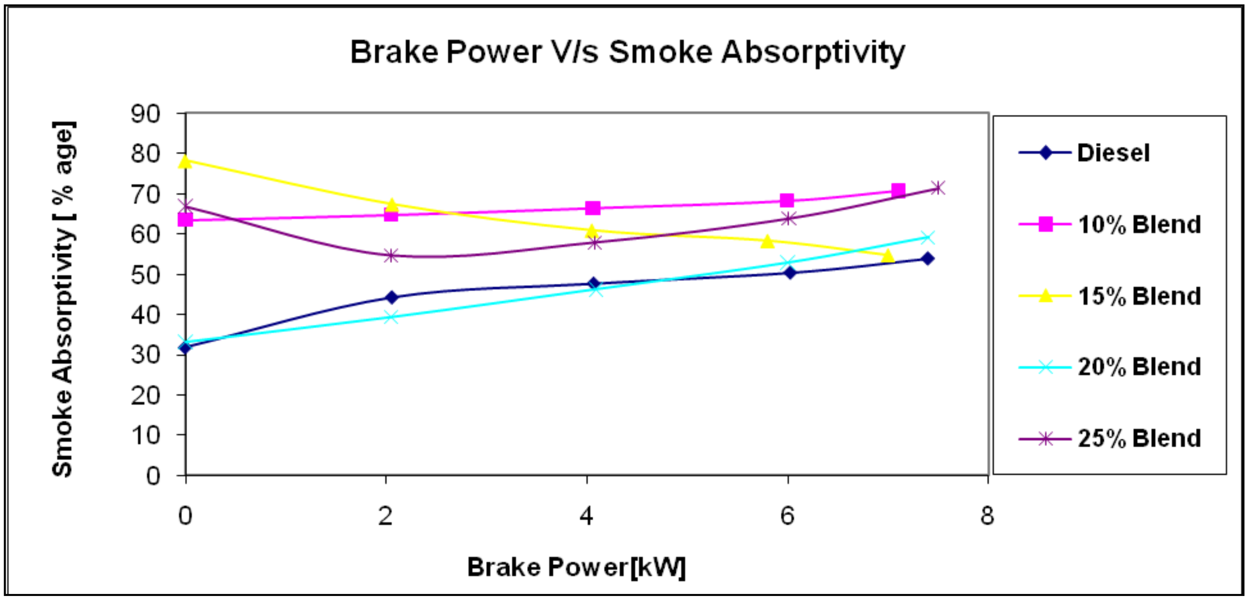


Figure 4.6.7 Variations of Smoke Absorptivity against the Brake Power for different Cardanol biodiesel **blends.**

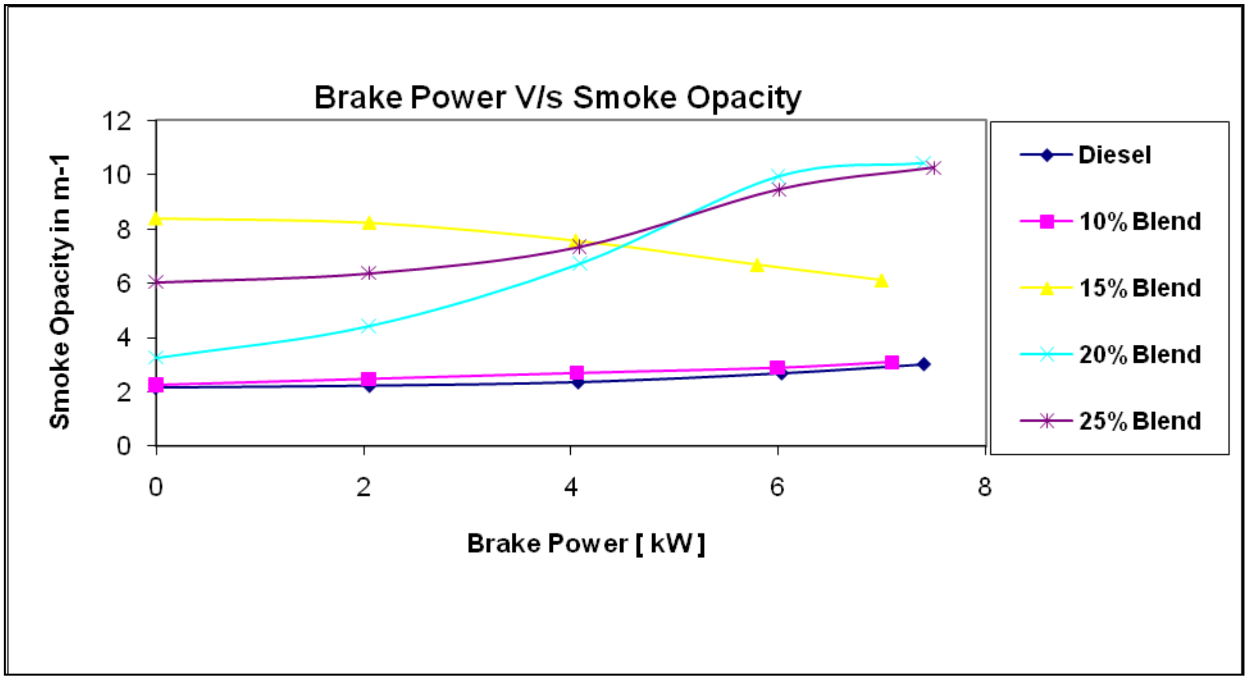


Figure 4.6.8 Variations of Smoke Opacity against the Brake Power for different Cardanol biodiesel blends.

CHAPTER-5

P E CHARECTERSTICS OF ALL THE THREE ENGINES AT 20%, CBD VOLUMETRIC BLENDS

5.1 GENERAL

From the previous chapter experimentation, results and considering the design aspects of the stationary diesel engine, and the regulations from our government that to use only 20% blend along with regular diesel fuel [73, 74]. This chapter presents the results and discussions of all the three engines at 20% CBD volumetric blends.

5.2 Performance characteristics of all engines at 20% CBD volumetric blends.

At the outset of this investigation, 20% CBD volumetric blend is considered as an ultimate blend for the diesel engine. On the other hand, considering emissions and performance characteristics, it is proved that up to 20% CBD Volumetric blends can be used in the diesel engine without any major hardware modifications.

5.2.1 Brake thermal efficiency v/s Load

Figure 5.1 depicts that the brake thermal efficiency increased with higher loads. In all cases, it increases with increased in load. This was due to reduction in heat losses and increase in brake power with increase in load. The brake thermal efficiency obtained for single cylinder and VCR at 20% cardanol biodiesel volumetric blends was less than that of twin cylinder diesel engine. This lower brake thermal efficiency obtained could be due to lower [both in single cylinder and VCR engines] brake power and increase in fuel consumption as compared to other two diesel engines. Another reason for higher brake power in the case of twin cylinder engine may be higher brake mean effective pressure.

5.2.2 Brake Specific Energy Consumption v/s load at 20% blends

From the figure 5.2, the brake specific energy consumption decreased by 30 to 40% approximately with increase in load conditions. This reverse trend was observed due to lower calorific value and higher viscosity with increase in biodiesel percentage in the blends.

The brake specific energy consumption decreased by 30 to 40% approximately at higher CR and 25 to 30% at lower CR with increases in brake power. This reverse trend was observed due to lower calorific value with increase in biofuel percentage in the blends.

The BSEC obtained for VCR engine at 18:1 Compression ratio was 25% more compared to twin cylinder engine at no load conditions. And 8-10% higher BSEC in twin cylinder engine compared to other two engines at full load conditions. The reason for this reverse trend may be higher brake mean effective pressure.

5.2.3 NOx Emissions v/s load at 20% blends

From the figure 5.3, it was observed that slight variations of NOx emissions occur in all engines at 0% load and 100% load conditions; these variations may be due to malfunctioning of biofuel mixture. NO_x emissions are sensitive to the spry characteristics, temperature and oxygen. The spry characteristics of a fuel depend on droplet size, penetration rate, evaporation rate, degree of mixing with the air etc. A change in any of these properties may change NO_x production.

5.2.4 HC Emissions v/s load at 20% blends

From the figure 5.4 it has been observed that lower (30-50%) hydrocarbon emissions occur in the case of VCR engine at 18:1 CR compared to single cylinder and twin cylinder engines.This may be due to proper burning of fuel at higher compression ratio. Another reason for this could be incomplete combustion and physical properties of the CBD.

5.2.5 CO Emissions v/s load at 20% blends

From the figure 5.5, it has been observed that the minimum and maximum CO produced is 0.03-0.08%. At higher loads, CO emissions slightly decreased. At elevated temperature, performance of the engine improved with relatively better burning of the fuel resulting in decreased CO.

The carbon monoxide emissions at different load conditions in different engines are not uniform. The reason for this could be malfunctioning of CBD volumetric blends in different injection systems, which may be due to change of operating parameters in CI engines.

5.3 Closer

- The brake thermal efficiency obtained for single cylinder and VCR at 20% cardanol biodiesel volumetric blends was less than that of twin cylinder diesel engine. This lower brake thermal efficiency obtained could be due to lower [both in single cylinder and VCR engines] brake power and increase in fuel consumption as compared to other two diesel engines. Another reason for higher brake power in the case of twin cylinder engine may be higher brake mean effective pressure.

- The BSEC obtained for VCR engine at 18:1 compression ratio was 25% more compared to twin cylinder engine at no load conditions and the BSEC for twin cylinder engine was 10% higher compared to other two engines at full load conditions. The reason for this reverse trend may be due to higher brake mean effective pressure.
- It is observed that slight variations of NOx emissions occur in all engines at 0% load and 100% load conditions; these variations may be due to malfunctioning of biodiesel mixture. NO_x emissions are sensitive to the spry characteristics, temperature and oxygen. The spry characteristics of a fuel depend on droplet size, penetration rate, evaporation rate, degree of mixing with the air etc. A change in any of these properties may change NO_x production.
- From the results it is observed that hydrocarbon emissions are lower (30-50%) in the case of the VCR engine at 18:1 CR compared to single cylinder and twin cylinder engines. This could be due to proper burning of fuel at higher compression ratio. Another reason for this could be incomplete combustion and physical properties of the CBD.
- CO were nominal up to 20% cardanol biodiesel valumetric blends.
- From this work it is proved that up to 20% CBD volumetric blends can be used in the diesel engine without any major modifications.

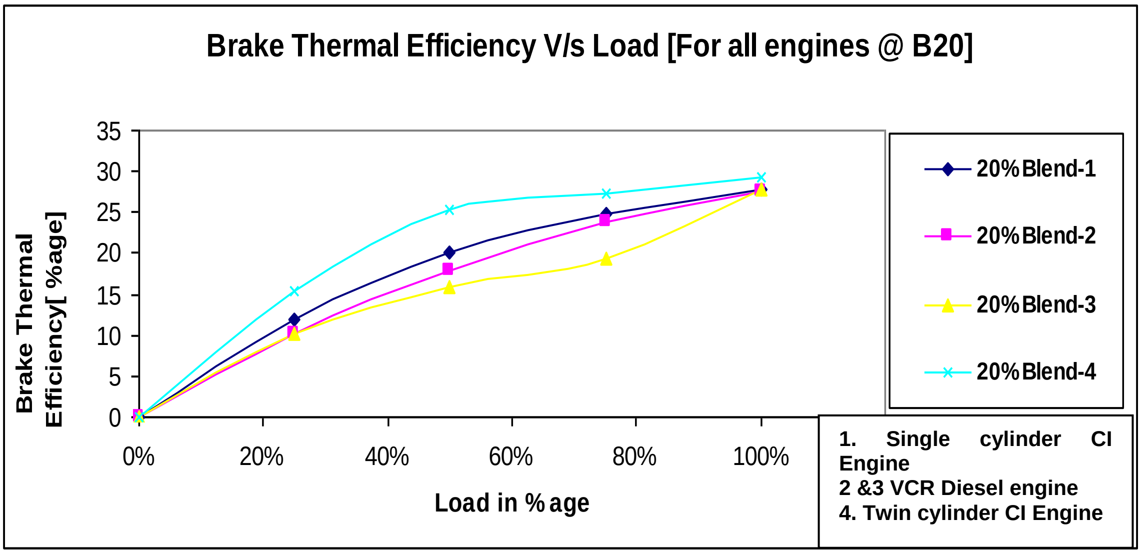


Figure 5.1 Brake thermal efficiency v/s load at 20% blends

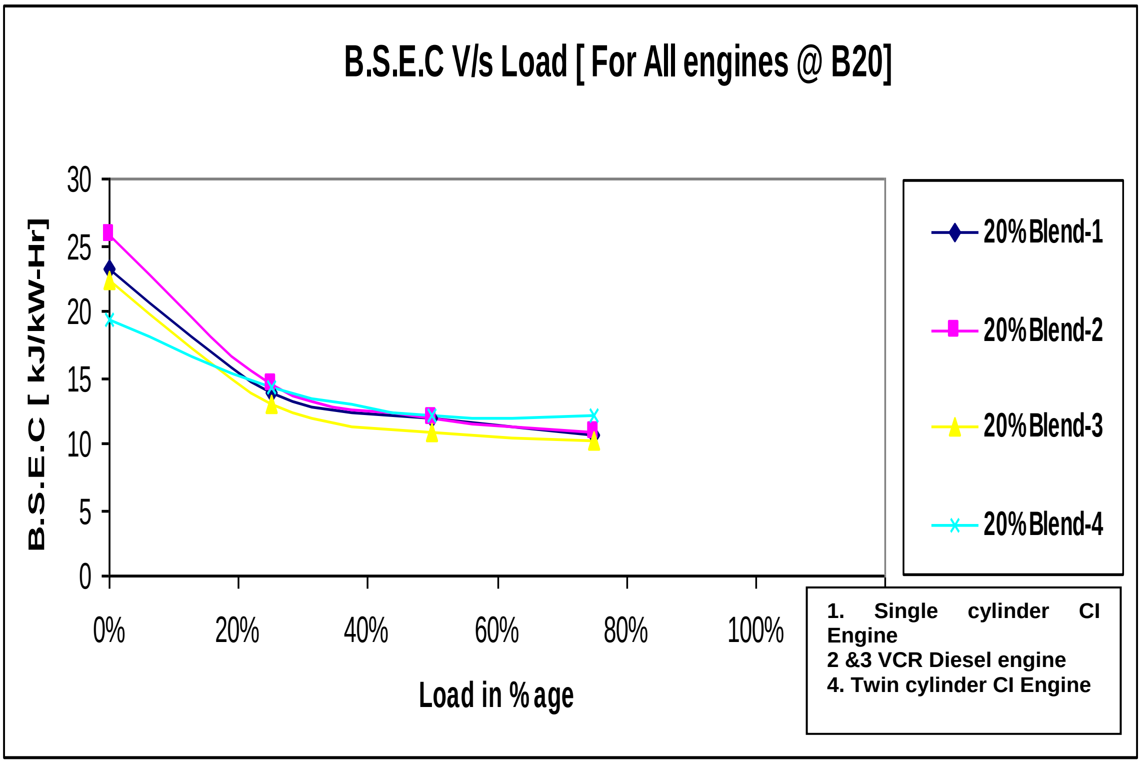


Figure 5.2 Brake Specific Energy Consumption v/s load at 20% blends

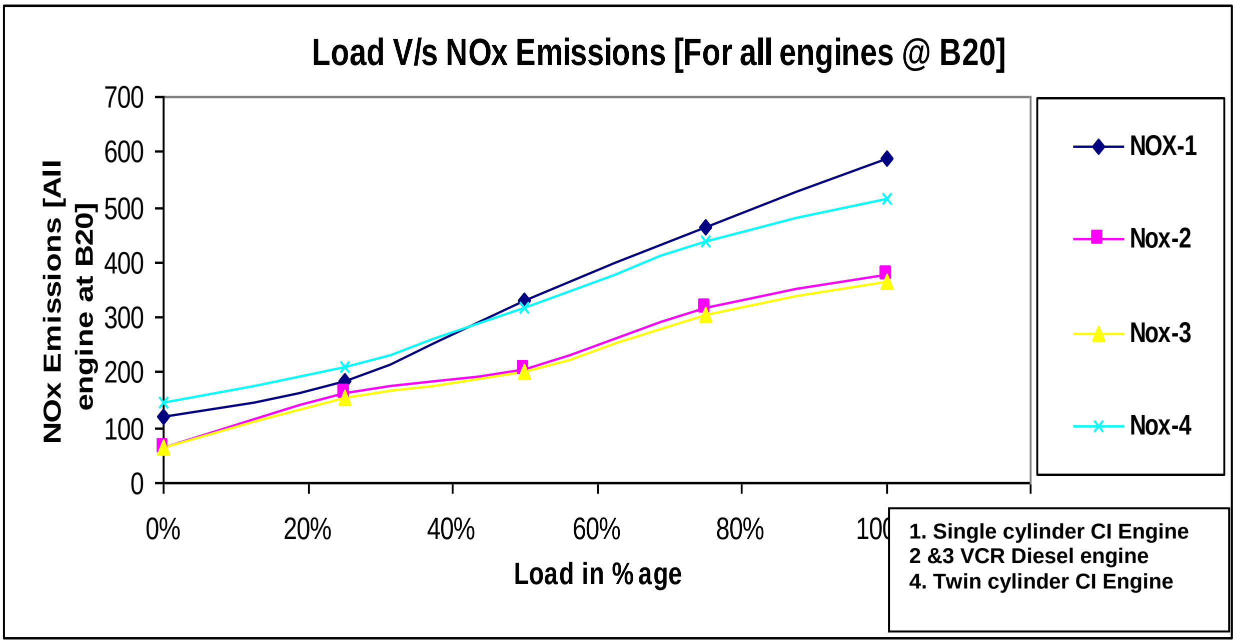


Figure 5.3 NOx Emissions v/s load at 20% blends

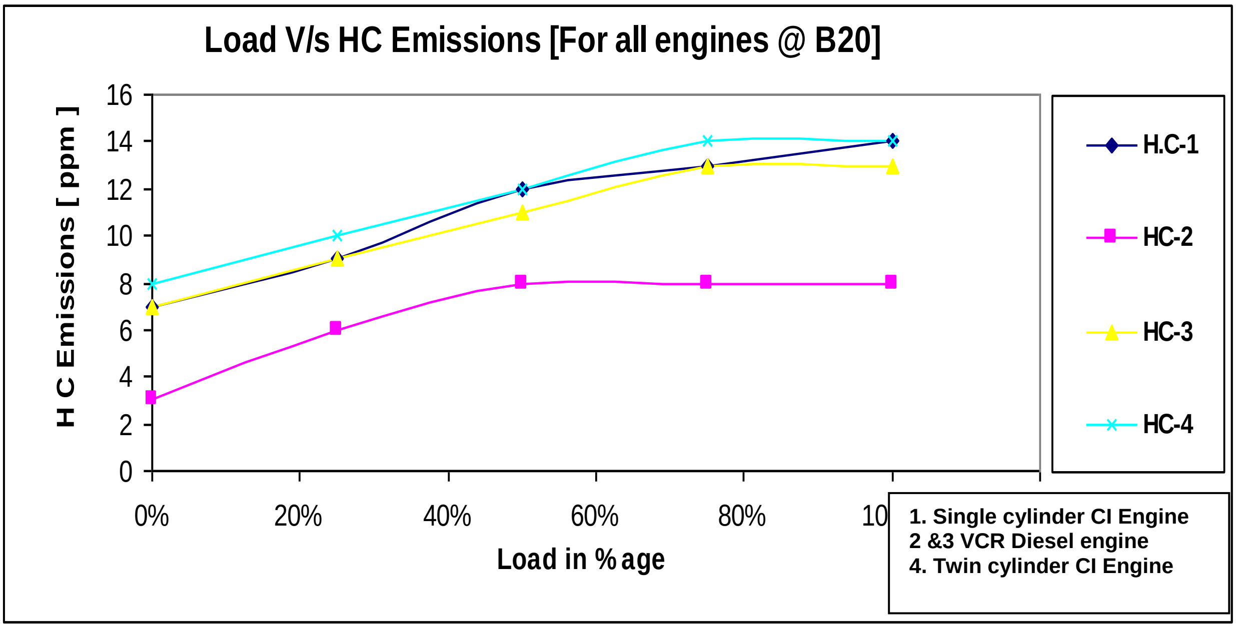


Figure 5.4 HC Emissions v/s load at 20% blends

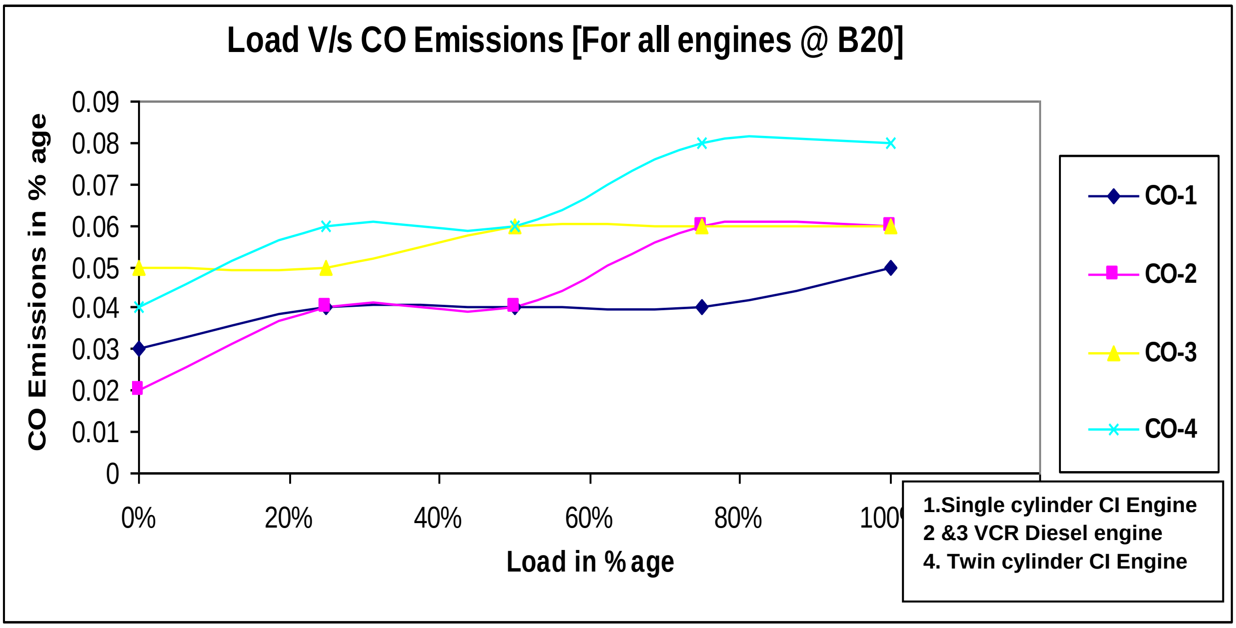


Figure 5.5 CO Emissions v/s load at 20% blends

CHAPTER-6

CONCLUSIONS AND SCOPE FOR FUTURE STUDY

CONCLUSIONS

In the present work cardanol biodiesel and its blends were identified for experimental investigation in single cylinder CI engine, Variable Compression Ratio CI engine and double cylinder CI engine. The important fuel properties of cardanol biodiesel volumetric blends and comparisons of properties of cardanol biofuel and their blends with diesel oil were studied.

The detailed conclusions drawn from the present investigations are as fallows.

6.1 GENERAL

- Cashew trees are agro forestry type; grow even in drought prone areas abundantly in all parts of India. By cultivating this type of agro forestry multi utility crop, it is possible to reduce deforestation or afforestation.
- Cashew trees in India were planted for the protection of coastal dunes, sometimes in combination with wasteland recovery, almost exclusively on poor soils unsuitable for other crops.
- In the countries south of the Sahel with 600-800 mm annual rainfall, cashew is important as a tree to counterbalance desertification.
- *National Security:* Since it is made domestically, it reduces our dependence on foreign fuel.
- *National Economy:* Using biodiesel keeps our fuel buying currencies at home instead of bring spent. This reduces our trade deficit and creates jobs.
- The significant factor of cardanol biodiesel is its low cost, its abundance and its production as a byproduct of cashew nut industries. It is renewable, easily produced inexpensively in most regions of the world, and hence is used as a substitute for fossil diesel in this work.

6.2 BIOFUEL PROPERTIES

- The properties like density, viscosity, flash and fire points of cardanol biodiesel volumetric blends under test are higher, and their calorific values are lower and are in the range of 94-96%that of diesel.

6.3 SINGLE CYLINDER, VCR & TWIN CYLINDER DIESEL ENGINES

- It was observed that the brake specific energy consumption decreased by 30 to 40% approximately with increase in load conditions in single cylinder engine. BSEC decreases by 30 to 40% approximately at higher CR and 25 to 30% at lower CR with increase in brake power in VCR engine, and similar trend observed in the case of twin cylinder engine. This reverse trend is observed due to lower calorific value and higher viscosity with increase in biodiesel percentage in the blends.
- The brake thermal efficiency increases with higher BP. In all cases, it increases with increase in BP. This is due to reduction in heat losses and increase in brake power with increase in load. The brake thermal efficiency obtained for cardanol biodiesel volumetric blends is less than that of diesel. This lower brake thermal efficiency obtained could be due to lower calorific value and increase in fuel consumption as compared to diesel. Smoke density is nominal up to B20 and more at B25. The reason for this is the incomplete combustion.
- The exhaust gas temperature increases linearly form 180^{o} C at no load to $480\,^{o}$ C at full load conditions. This increasing trend of EGT is mainly because of generating more power and consumption of more fuel at higher loads.
- It was observed that NOx emissions (ppm) increase with increased proportion of blends and also with higher EGT. NO_x emissions are sensitive to the spry characteristics, temperature and oxygen. The spry characteristics of a fuel depend on droplet size, penetration rate, evaporation rate, degree of mixing with the air etc. A change in any of these properties may change NO_x production. This trend is mainly because of the presence of oxygen in biodiesel. This leads to more oxidation at higher temperature and is responsible for more No_x emissions. The NOx emissions at 17:1 compression ratio slightly lower than that of 18:1 CR. This is mainly because of lower exhaust gas temperature in the case of 17:1CR.

- It was observed that HC emissions are nominal up to B20, and more at B25, the reason for this being incomplete combustion and physical properties of the CBD.
- It was observed that the carbon monoxide emissions increase with higher blends, and increase slightly more after 20% blends. The minimum and maximum CO produced was 0.03-0.08%. At higher loads, except for 25 % blend, CO emissions slightly decreased. At elevated temperature, performance of the engine improved with relatively better burning of the fuel resulting in decreased CO.

6.4 COMPARISON OF RESULTS AT 20% BLENDS OF ALL THREE ENGINES

- The brake thermal efficiency obtained for single cylinder and VCR at 20% cardanol biodiesel volumetric blends is less than that of twin cylinder diesel engine. This lower brake thermal efficiency obtained could be due to lower [both in single cylinder and VCR engines] brake power and increase in fuel consumption as compared to other two diesel engines. Another reason for higher brake power in the case of twin cylinder engine may be due to higher brake mean effective pressure.
- The BSEC obtained for VCR engine at 18:1 compression ratio is 25% more compared to twin cylinder engine at no load conditions. The BSEC for twin cylinder engine is 8-10% higher compared to other two engines at full load conditions. The reverse trend may be due to higher brake mean effective pressure.
- Slight variations of NOx emissions are observed in all engines at 0% load and 100% load conditions; the reason for these variations may be malfunctioning of biodiesel mixture. NO_x emissions are sensitive to the spry characteristics, temperature and oxygen. The spry characteristics of a fuel depend on droplet size, penetration rate, evaporation rate, degree of mixing with the air etc. A change in any of these properties may change NO_x production.

- From the results it is observed that hydrocarbon emissions were lower (30-50%) in the case of VCR engine at 18:1 CR compared to single cylinder and twin cylinder engines.The reason for this may be due to proper burning of fuel at higher compression ratio. Another reason for this could be incomplete combustion and physical properties of the CBD.
- CO was nominal up to 20% Cardanol biodiesel valumetric blends.
- The present work reveals that cardanol biodiesel volumetric blends up to 20% can be used in the diesel engine without any major modifications.

6.5 SCOPE FOR FUTURE WORK

- Suitable catalyst or additives required to reduce emission level above 25% CBD.
- Some additives such as LZ-8005, made in the form Lubrizol, may be added into the fuel for testing the engine performance and emission, to study the smoke emission and possible improvement of thermal efficiency of the engine.
- Combustion temperature, and therewith NOx levels, can be lowered by running lean, pre-mixed or by using exhaust gas recirculation (EGR) to change the trapped mass composition.
- Performance evaluation of the engine with conditioned oils can be carried out in a pre-chamber type IDI engine, to study combustion efficiency.
- The studies can be conducted on stationary engines (both in single and multi cylinder engines) with
  1) Increasing compression ratio.
  2) Modifying fuel injection timings.
  3) Increase/decrease fuel injection pressure and injection rate.

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APPENDIX

APENDIX - I

RESULTS OF SINGLE CYLINDER ENGINE

Table S1: Brake power v/s load

Load (N-mtr)	Diesel	10% Blend	15% Blend	20% Blend	25% Blend
0	0	0	0	0	0
5	0.81	0.796	0.795	0.795	0.79
10	1.6	1.575	1.58	1.576	1.57
15	2.81	2.396	2.3	2.22	2.15
20	3.14	3.11	3.02	2.99	2.82

Table S2.B S E C v/s load

Load (N-mtr)	Diesel	10% Blend	15% Blend	20% Blend	25% Blend
0	-------	---------	--------	---------	-------
5	24.46	24.199	23.866	23.121	23.021
10	15.53	13.759	13.813	13.745	13.568
15	14.1	12.059	12.042	12.018	12.011
20	14	10.861	10.752	10.552	10.471

Table S3. Air fuel ratio v/s Load

Load (N-mtr)	Diesel	10% Blend	15% Blend	20% Blend	25% Blend
0	0.10	0.11	0.12	0.12	0.12
5	0.48	0.48	0.42	0.42	O.42
10	0.6	0.54	0.57	0.54	0.66
15	0.78	0.72	0.66	0.78	0.9
20	0.96	0.9	0.96	0.96	1.14

Table S4.B.T.E V/S Load

Load (N-mtr)	Diesel	10% Blend	15% Blend	20% Blend	25% Blend
0	0	0	0	0	0
5	14.71	12.5	12.4	11.8	11.1
10	23.17	20.35	20.24	20.06	20.01
15	29.24	25.42	24.88	24.76	24.2
20	30.08	28.1	27.96	27.74	26.96

Table S5. Exhaust gas temperature v/s load

Load (N-mtr)	Diesel	10% Blend	15% Blend	20% Blend	25% Blend
0	196	180	194	204	182
5	247	234	240	247	243
10	323	305	300	286	309
15	394	370	382	387	392
20	430	478	465	468	454

Table S6 Load V/s various emissions levels

Sl.No	Load	Diesel			10% Blend			15% Blend			20% Blend			25% Blend		
	(Nmtr)	H.C	NO_X	CO	H.C	NO_X	CO	H.C	NO_X	CO	H.C	NO_X	CO	H.C	NO_X	CO
		%	(ppm)	%	%	(ppm)	%	%	(ppm)	%	%	(ppm)	%	%	(ppm)	%
1	0	5	80	0.03	4	110	0.04	7	119	0.05	15	119	0.04	24	145	0.06
2	5	6	140	0.03	7	168	0.04	12	172	0.05	17	183	0.04	23	201	0.06
3	10	10	216	0.02	11	275	0.04	16	310	0.04	22	330	0.04	26	340	0.05
4	15	17	366	0.02	18	432	0.03	23	456	0.04	27	463	0.04	29	480	0.05
5	20	20	424	0.02	26	560	0.03	29	580	0.04	34	588	0.04	36	605	0.05

APENDIX - II

RESULTS OF VCR ENGINE

COMPRESSION RATIO 18:1

Table V1 Brake Power (kW) Vs Load

Load % age	Diesel	10%Blend	15% Blend	20% Blend	25% Blend
0%	0	0	0	0	0
25%	0.86	0.8	0.8	0.79	0.8
50%	1.71	1.7	1.6	1.61	1.65
75%	2.53	2.53	2.43	2.41	2.32
100%	3.41	3.39	3.33	3.32	3.3

Table V2 Smoke density levels Vs Load:

Load % age	Diesel	10%Blend	15% Blend	20% Blend	25% Blend
0%	0.19	0.17	0.27	0.34	0.44
25%	0.22	0.2	0.25	0.39	0.48
50%	0.27	0.28	0.32	0.35	0.55
75%	0.37	0.42	0.49	0.57	0.68
100%	0.4	0.48	0.57	0.66	0.72

Table V3 Exhaust gas temp (in ^{o}C) V/s load

Load in % age	Diesel	10%Blend	15% Blend	20% Blend	25% Blend
0	180	185	178	184	186
25	261	262	263	272	278
50	292	296	286	290	296
75	374	389	342	366	366
100	400	414	390	396	399

Table V4 Brake thermal efficiency (in % age) V/s Load:

Load in % age	Diesel	10%Blend	15% Blend	20% Blend	20% Blend	25% Blend
0	0	0	0	0	0	0
25	12.48	11.85	11.38	10.11	10.08	10.01
50	19.98	18.98	18.12	18.1	17.82	17.74
75	26.23	25.36	25.12	23.92	23.71	23.65
100	28.32	28.3	28.3	27.84	27.64	27.01

TableV5 BSEC [kJ/(kW-hr)10^{-3}] V/s load

Load in % age	Diesel	10%Blend	15% Blend	20% Blend	25%Blend
0	-------	---------	--------	---------	-------
25	29.326	26.99	25.84	25.75	25.34
50	19.024	15.79	14.9	14.5	14.23
75	13.989	12.46	12.07	11.84	11.65
100	12.56	11.22	11.04	10.88	9.86

Table V6 Load V/s various emission levels

Sl.No	Load In %age	Diesel			10% Blend			15% Blend			20% Blend			25% Blend		
		H.C %	NO_X (ppm)	Co %	H.C %	NO_X (ppm)	Co %	H.C %	NO_X (ppm)	Co %	H.C %	NO_X (ppm)	Co %	H.C %	NO_X (ppm)	Co %
1	0%	3	50	0.03	3	57	0.03	3	56	0.03	3	66	0.05	4	98	0.06
2	25%	4	130	0.02	5	138	0.03	5	140	0.03	6	162	0.05	7	196	0.06
3	50%	6	180	0.02	7	196	0.03	8	199	0.03	8	208	0.06	9	270	0.07
4	75%	7	260	0.02	8	278	0.02	8	308	0.03	8	316	0.06	9	384	0.07
5	100%	8	310	0.02	8	328	0.02	8	340	0.03	8	378	0.06	9	450	0.08

COMPRESSION RATIO 17:1

TableV7 Brake Power (kW) Vs Load

Load in % age	Diesel	10%Blend	15% Blend	20% Blend	25% Blend
0	0	0	0	0	0
25	0.86	0.79	0.79	0.76	0.72
50	1.61	1.6	1.6	1.51	1.48
75	2.42	1.98	1.93	1.83	1.78
100	3.21	3.19	3.15	3.13	3.09

Table V8 Smoke density levels (HSU Units) V/s Load

Load in % age	Diesel	10%Blend	15% Blend	20% Blend	25% Blend
0	0.06	0.24	0.48	0.53	0.54
25	0.08	0.41	0.53	0.56	0.58
50	0.16	0.46	0.64	0.61	0.66
75	0.3	0.49	0.55	0.69	0.76
100	0.41	0.64	0.72	0.9	1.1

Table V9 Exhaust gas temp V/s load

Load in % age	Diesel	10%Blend	15% Blend	20% Blend	25% Blend
0	188	188	184	185	184
25	198	199	229	199	199
50	252	275	276	268	266
75	289	290	290	289	288
100	360	382	389	390	399

Table V10 Brake thermal efficiency V/s Load

Load in % age	Diesel	10%Blend	15% Blend	20% Blend	25% Blend
0	0	0	0	0	0
25	11.48	10.85	10.38	10.11	10.08
50	19.88	17.25	16.12	15.98	15.94
75	25.63	21.66	21.21	19.3	17.9
100	31.45	28.5	28.14	27.84	27.12

TableV11BSEC [kJ/ (kW-hr) ×10^{-3}] V/s load

Load in % age	Diesel	10%Blend	15% Blend	20% Blend	25%Blend
0	-------	---------	--------	---------	-------
25	29.326	26.99	25.84	22.37	22.04
50	21.054	15.79	14.9	13	12.13
75	13.989	12.46	12.07	10.84	10.07
100	12.26	11.22	11.04	10.11	9.32

Table V12 Load V/s various emission levels

Sl.No	Load In %age	Diesel			10% Blend			15% Blend			20% Blend			25% Blend		
		H.C %	NO_X (ppm)	Co %	H.C %	NO_X (ppm)	Co %	H.C %	NO_X (ppm)	Co %	H.C %	NO_X (ppm)	Co %	H.C %	NO_X (ppm)	Co %
1	0%	3	50	0.04	3	55	0.03	4	52	0.04	4	63	0.05	5	97	0.06
2	25%	5	125	0.03	5	130	0.04	5	137	0.04	6	155	0.05	5	195	0.06
3	50%	6	174	0.03	7	188	0.04	9	188	0.04	9	201	0.06	9	269	0.07
4	75%	8	250	0.03	9	278	0.04	9	288	0.04	9	307	0.06	9	382	0.07
5	100%	9	306	0.03	9	318	0.04	9	321	0.04	9	366	0.06	9	440	0.08

APENDIX III

RESULTS OF TWIN CYLINDER ENGINE

Table T1 BRAKE POWER V/s Load

Sl.No	Load	Diesel	10% Blend	15% Blend	20% Blend	25% Blend
1	0%	0	0	0	0	0
2	25%	2.06	2.05	2.06	2.05	2.05
3	50%	4.07	4.06	4.05	4.09	4.08
4	75%	6.03	5.99	5.8	6	6.01
5	100%	7.4	7.1	7	7.4	7.5

Table T2 Brake thermal efficiency Vs Load

Sl.No	Load	Diesel	10% Blend	15% Blend	20% Blend	25% Blend
1	0%	0	0	0	0	0
2	25%	15.07	17.59	15.12	15.4	14.64
3	50%	32.51	24.74	24.04	25.221	24.12
4	75%	48.18	30	29.6	27.368	27.76
5	100%	50.35	29.87	29.78	29.31	28.13

Table T4 Load V/s Exhaust gas temperature in Degrees C

Sl.No	Load	Diesel	10% Blend	15% Blend	20% Blend	25% Blend
1	0%	186	185	190	199	190
2	25%	237	241	240	243	247
3	50%	301	302	306	309	323
4	75%	372	380	383	392	398
5	100%	463	474	479	478	479

Table T3 Load V/s Smoke Opacity & Absorptivity

Sl.No	Load	Diesel		10% Blend		15% Blend		20% Blend		25% Blend	
	In %age	N	K	N	K	N	K	N	K	N	K
1	0%	31.9	2.15	63.5	3.1	78.3	4.66	33.2	4.56	66.9	4.98
2	25%	44.3	2.3	64.8	3.44	67.4	4.85	39.4	4.95	54.6	5.01
3	50%	47.7	2.45	66.5	3.66	60.9	5.1	46.3	5.13	57.9	5.21
4	75%	50.4	2.6	68.3	3.96	58.3	5.4	52.9	5.52	63.9	5.61
5	100%	53.9	3.1	70.8	4.23	54.7	5.96	59.2	5.74	71.5	5.97

Table T5 Load V/s No$_x$ Emissions

Sl.No	Load	Diesel	10% Blend	15% Blend	20% Blend	25% Blend
1	0%	99	137	146	148	148
2	25%	178	184	196	210	256
3	50%	282	295	297	318	465
4	75%	396	402	415	436	516
5	100%	396	404	486	515	678

Table T6 Load V/s HC Emissions

Sl.No	Load	Diesel	10% Blend	15% Blend	20% Blend	25% Blend
1	0%	2	3	6	8	8
2	25%	5	7	8	10	12
3	50%	5	8	8	12	14
4	75%	7	9	10	14	16
5	100%	9	9	10	14	17

Table T7 Load V/s Co Emissions

Sl.No	Load	Diesel	10% Blend	15% Blend	20% Blend	25% Blend
1	0%	0.02	0.03	0.04	0.04	0.06
2	25%	0.02	0.03	0.04	0.06	0.08
3	50%	0.04	0.04	0.06	0.06	0.09
4	75%	0.05	0.04	0.06	0.08	0.09
5	100%	0.05	0.03	0.07	0.08	0.09

PUBLICATIONS

LIST OF PUBLICATIONS BASED ON THE RESEARCH WORK

I. Publications in International Journals

1. Mallikappa, Rana Pratap Reddy, Ch.S.N.Murthy,"*Performance and Emission Characteristics of Double Cylinder CI Engine Operated with Cardanol Bio fuel Blends*". Elsevier - Renewable Energy 38 (2012) 150 - 154
2. Mallikappa, Rana Pratap Reddy, Ch.S.N.Murthy, "*Performance and Emission Characteristics of DI CI Engine Operated with Cardanol Bio fue.l*" International Journal on Mechanical & Automobile Engineering,(IJMAE) Volume 12, Issue No 01, (2010) 21-29.
3. Mallikappa, Rana Pratap Reddy, Ch.S.N.Murthy "*Performance and Emission Characteristics of Stationary CI Engine with Cardanol Biofuel blends*". International Journal of Scientific and Engineering Research, Volume 2, Issue 4, (2011) 56-61.
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II. Publications in International/National Conferences

1. Mallikappa, Rana Pratap Reddy. Ch.S.N.Murthy, "*Performance and emission studies of non- road VCR type CI engine with methyl esters of cardanol oil*". International symposium on "Emerging trends in environment, health and safety management in mining and mineral based industries" NITK, Surathkal, Karnataka India. (2010) 182-192
2. Mallikappa , Rana Pratap Reddy, Ch.S.N.Muthy, "*Experimental Investigation on Performance and Emissions Characteristics of Non-road CI Engine with Cardnol Bio fuel blends.*" National Conference on Advances in Mechanical Engineering MIT, Manipal, Karnataka India. (2011), 22.

III Papers accepted for publications in International Journals

1. Mallikappa, Rana Pratap Reddy, Ch.S.N.Murthy, "Performance and Emission Studies of Non- road Multi cylinder CI Engine Operated with Cardanol Bio fuel blends". IJMAE- [SERC-IJMAE-JPH11-04F]

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03	Project Engineer	M/S Pipeline Engineers & Traders, Bangalore	1995	1998
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PUBLISHED JOURNAL/ SYMPOSIUM/ CONFERENCE PAPERS

1. Mallikappa, Rana Pratap Reddy, Ch.S.N.Murthy,"*Performance and Emission Characteristics of Double Cylinder CI Engine Operated with Cardanol Bio fuel Blends*". Elsevier - Renewable Energy 38 (2012) 150 - 154
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