PERFORMANCE ANALYSIS OF PALM, JATROPHA AND MORINGA BIODIESELS IN A DIESEL ENGINE

MD. MOFIJUR RAHMAN

DISSERTATION SUBMITTED IN FULFILMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF ENGINEERING SCIENCE

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2013

ABSTRACT

The global energy consumption is expected to grow in a faster rate than the population growth. By 2030, an increase of 53% of global energy consumption and 39% of greenhouse gases emissions from fossil fuels are anticipated. Therefore, it has become a global agenda to develop clean alternative fuels which are domestically available, environmentally acceptable and technically feasible. As an alternative fuel, biodiesel seems as one of the best choices among other sources due to its environment friendly aspect and similar functional properties as diesel fuel. This research aims to produce biodiesel from some edible and non-edible oils that are either readily available or have native distribution in Malaysia. These oils include; Palm (*Elaeis guineensis*), *Jatropha curcas and Moringa oleifera* oils. This was followed by a detailed investigation of physic-chemical properties of the produced methyl esters such as kinematic viscosity, density, flash point, cloud point, pour point, cold filter plugging point, viscosity index and oxidation stability. This research also discusses the concept of biodiesel-diesel blending to improve some of the properties. Moreover, 5%, 10%, 15% and 20% by volume blends of Palm, *Jatropha curcas and Moringa oleifera* were used to evaluate their performance in a Mitsubishi Pajero turbocharged diesel engine. According to the results of the investigation, the produced methyl esters meet biodiesel standard specification. Moreover, blending of biodiesel with diesel fuel improves their fuel properties. The results of engine performance indicated that over the entire range of speed, biodiesel blended fuels give average reduction in torque, brake power and increased brake specific fuel consumption values compared to diesel fuel. In case of engine emission, biodiesel blended fuels give an average reduction in carbon monoxide and hydrocarbon emissions whereas slightly increased nitric oxides and carbon dioxides emissions respectively compared to diesel fuel. Overall, Palm biodiesel blended fuel showed better performance than *Jatropha curcas* and *Moringa oleifera* biodiesel blended fuels. In conclusion, Palm, *Jatropha curcas* and *Moringa oleifera* are potential feedstock for biodiesel production, and up to 20% of their blends should be considered to replace diesel fuel without engine modification to reduce the dependency on petro-diesel and produce cleaner exhaust emissions.

ABSTRAK

Kadar penggunaan tenaga global dijangka berkembang lebih cepat daripada kadar pertumbuhan penduduk. Pada tahun 2030, peningkatan dijangkakan sebanyak 53% dalam penggunaan tenaga global dan peningkatan juga dijangkakan sebanyak 39% dalam pelepasan gas rumah hijau daripada bahan api fosil. Oleh itu, ini menjadi satu agenda global untuk membangunkan bahan api alternatif bersih yang terdapat dalam negara, yang mesra alam-sekitar dan yang boleh dilaksanakan secara teknikal. Sebagai bahan api alternatif, biodiesel merupakan salah satu pilihan yang terbaik di kalangan sumber-sumber lain kerana sifat mesra alam-sekitar dan ia mempunyai ciri-ciri fungsi yang sama seperti bahan api diesel. Kajian ini bertujuan untuk menghasilkan biodiesel daripada beberapa minyak yang boleh dimakan dan yang tidak boleh dimakan, sama ada yang sedia-ada atau yang mempunyai pengedaran di dalam Malaysia. Minyak ini termasuk; minyak sawit, *Jatropha curcas* dan *Moringa oleifera*. Ini diikuti dengan penyiasatan sifat fizik-kimia untuk biodiesel yang dihasilkan, separti kelikatan kinematic, ketumpatan, takat kilat, takat tidak-larut, takat boleh-dituang, sejuk penapis memasang mata, indeks kelikatan dan kestabilan pengoksidaan. Kajian ini juga membincangkan konsep campuran biodiesel-diesel untik memperbaiki beberapa ciri-ciri bahan suapan ini. Selain itu, campuran 5%, 10%, 15% dan 20% sawit, *Jatropha curcas* dan *Moringa oleifera* telah dijalankan untuk menilai prestasi mereka dalam Enjin Diesel Turbo, iaitu Mitsubishi Pajero. Menurut penyiasatan, biodiesel yang dihasilkan memenuhi spesifikasis piawai biodiesel dan campuran biodiesel dengan diesel meningkatkan sifat-sifat bahan api tersebut. Keputusan prestasi enjin menunjukkan bahawa pada pelbagai kelajuan, bahan api biodiesel yang dicampur memberikan pengurangan tork purata, pengurangan kuasa brek dan meningkatkan nilai-nilai penggunaan bahan api brek tertentu berbanding dengan bahan api diesel. Dalam kes pelepasan gas enjin, bahan api campuran biodiesel memberikan pengurangan yang berpurata dalam pelepasan karbon monoksida dan pelepasan hidrokarbon. Manakala terdapat sedikit peningkatan dalam pelepasan nitrus oksida dan pelepasan karbon dioksida berbanding dengan bahan api diesel. Keseluruhan, campuran bahan api biodiesel menunjukkan prestasi yang lebih baik berbanding dengan campuran bahan api biodiesel sawit, *Jatropha curcas* dan *Moringa oleifera*. Kesimpulannya, sawit, *Jatropha curcas* dan *Moringa oleifera* adalah bahan-bahan mentah yang berpotensi untuk pengeluaran biodiesel, dan sebanyak 20% daripada campuran bahan-bahan tersebut boleh menggantikan bahan api diesel tanpa penguabahsuaian enjin untuk mengurangkan pergantungan kepada petro-diesel dan akan menghasilkan pelepasan ekzos yang bersih.

University of Malaya

ORIGINAL LITERARY WORK DECLARATION

Name of the candidate: **Md. Mofijur Rahman (AA 3181159)**

Registration/Matric No: **KGA110004**

Name of the Degree: **Master of Science in Engineering**

Title of Thesis: **Experimental Studies of Biodiesel Fuel from Edible and Non-Edible Oil Sources in a Diesel Engine**

Field of Study: **Energy**

I do solemnly and sincerely declare that:

(1) I am the sole author/ writer of the work;
(2) This work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealings and any expert or extract from or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the work and tis authorship has been acknowledged in this work;
(4) I do not have any actual knowledge nor do I ought to reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this work to the University of Malaya (UM), who henceforth shall be the owner of the copyright in this work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained actual knowledge;
(6) I am fully aware that if in the course of making this work I have infringed any copyright whether internationally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature Date:

Subscribed and solemnly declared before,

Witness Signature

Name:

Designation

ACKNOWLEDGEMENTS

In the name of Allah, the most Merciful and Generous. Should all the praises upon him, for giving me the fortitude and aptitude to complete this thesis.

I would like to special thanks to my supervisors Professor Dr. Masjuki Hj. Hassan and Dr. Md. Abul Kalam for their helpful guidance, encouragement and assistance throughout this works. I also express my gratitude to the Ministry of Higher Education (MOHE) for HIR Grant for the financial support through project no. UM.C/HIR/MOHE/ENG/07. I also would like to convey appreciation to all lectures and staff of the Department of Mechanical Engineering, University of Malaya for giving opportunity to prepare and conduct this research. I also would like to thank Mr. Abdelaziz Emad Atabani and all members in "Centre for Energy Sciences" research group for their valuable ideas and discussion.

Additional Thanks to Mr. Sulaiman Ariffin, Mr. Kamarul Bahrin Bin Musa, Mr. Asri and Mr. Nur Azam Ali for their technical help and assistance.

Last but not least, take pleasure in acknowledgement the continued encouragement and moral support of my parents, my brothers and sisters and my wife. Also I would like to thank my research partners for their encouragement and support. Their help, advices and ideas had contributed a lot toward the success of this thesis.

Dedicated to my beloved

Father, ***Md. Abdur Rashid Forazy***

Mother, ***Rahima Khatun***

For their unconditional love and encouragement

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION

ASTM	American Society of Testing Materials
BP	Brake Power
BSFC	Brake Specific Fuel Consumptions
BTE	Brake Thermal Efficiency
CI	Compression Ignition
cm	Centimeter
CMOO	Crude *Moringa Oleifera* Oil
CPO	Crude Palm Oil
CJCO	Crude *Jatropha Curcas* oil
CO	Carbon Monoxide
CO_2	Carbon Dioxides
DF	Diesel Fuel
DI	Direct Injection
DOE	Department of Environment
USEIA	United States Energy Information Administration
EPA	Energy Protection Agency
EN	European Union
FAME	Fatty Acid Methyl Ester
h	Hour
HC	Hydrocarbon
IC	Internal Combustion
IEA	International Energy Agency
JB	Jatropha Biodiesel

kg	Kilogram
kW	Kilowatt
MB	Moringa Biodiesel
MJ	Mega Joule
mm	Millimeter
MPOB	Malaysian Palm Oil Board
Mtoe	Million Tons of Oil Equivalents
NEB	National Energy Board
NO	Nitric Oxide
NOx	Oxides of Nitrogen
OECD	Organization for Economic Co-operation and Development
PB	Palm Biodiesel
PM	Particulate Matter
ppm	Part Per Million
rpm	Revolution Per Minute
SAE	Society of Automotive Engineers

CHAPTER 1

INTRODUCTION

1.0 Introduction

1.1 Overview of Global Energy Scenario

It is one of the known facts that the advancement in modern economics through agricultural, telecommunication, transportation, industrial sectors, etc. is heavily depends upon energy. Consequently, worldwide energy consumption rate is growing faster than the population growth rate. For many countries, this ever growing increase of energy demand is becoming a critical issue. Usually, global energy demand is fulfilled by natural gas, crude oil, coal and other resources. Among them, gas and oil are largely used in combustion engines and as raw material for manufacturing plastic and other chemicals, too. At the present time, transportation sector heavily depends upon petroleum or crude fossil oil. All over the world, petroleum has become a dependent source due to having high density and better handling facility. They are a vital utility for a country's industrial economy.

World's energy map is changing. These changes have potentially persuasive consequences over the energy markets and trade. Global energy demand increases by more than one-third over the period to 2035 with India, China, and the Middle East responsible for 60% of the increase. Although, energy demand barely rises in OECD countries, there is a definite shift away from oil, coal (and, in some countries, nuclear) towards natural gas and renewable energy resources. Regardless of the growth in low carbon sources of energy, fossil fuels still dominating the global energy mix, supported by large subsidies such as $523 billion in 2011, 30% more than that of 2010 and six times more than subsidies provided for renewable. According to the International Energy Agency (IEA, 2012), by the year 2030 global energy consumption will increase by 53%. The main source of energy is fossil fuel fulfilling 87% of the demand, amongst other energy sources crude oil supplies 33.06%, coal 30.34% and natural gas 23.67% respectively. Nuclear energy, hydropower and renewable energy supplies very small percentages of the energy demand (4.88%, 6.44% and 1.58% of total energy usages respectively). The world's primary fuel consumption has doubled within 1980 to 2011. In 1980 energy consumption was 6,630 million tons of oil equivalents (Mtoe) which rose to 12274.6 Mtoe in 2011 (BP, 2012).

1.2 Overview of Malaysian Energy Scenario

According to British petroleum statistics; Malaysia's primary energy consumption has increased to 62.9 Mtoe in 2010 from 48.6 Mtoe in 2001, which is an average increase of 3.6% per annum. But in this period of time, oil production in Malaysia has decreased to 32.1 Mtoe in 2010 from 32.9 Mtoe in 2001. But, oil consumption has increased to 25.3 Mtoe in 2010 from 22 Mtoe in 2001. Contrasting to oil, production of natural gas has increased to 59.8 Mtoe in 2010 from 42.2 Mtoe in 2001. Also, an increase in the corresponding consumption has been observed. The final energy demand is growing considerably high rate of 5.4% per annum. In this rate the final energy demand will be 83.5 Mtoe in 2020 from 33.9 Mtoe in 2003 (BP, 2012). In Malaysia, annual biodiesel production increased at a rate of 26.6% per annum. The production was 1.1 thousand barrel per day in 2006, which rose to 5.7 thousand barrel per day in 2009 (USEIA, 2010).

1.3 Increasing Environment Pollution

Emissions from burning petroleum derived fuels have a severe consequence on both the environment as well as human health (Oener and Altun, 2009). The united nation intergovernmental panel reported that, due to the greenhouse gas emission including methane, nitrogen oxides and carbon dioxides, global warming is increasing. It is forecasted that emission of the greenhouse gases (GHG) from fossil fuels will increase up to 39% in 2030 if no strict steps are taken to alleviate it. Air pollution is a phenomenon where chemical, physical or biological agents modify the natural characteristics of the atmosphere. The types of pollutants are particulate matter and noxious gases such as sulfur dioxide, carbon monoxide, nitrogen oxides, and chemical vapors. All over the world, air pollution is heavily responsible for huge number of health problems and respiratory diseases. Mobile sources e.g. vehicles, stationary sources for instance factories and open burning of wastes like municipal and industrial wastes; are the three major sources of air pollution in Malaysia, whereby contributing to at least 70–75 %, 20–25 % and 3–5 %, respectively. According to the Department of the Environment (DOE, 2010), Malaysia, in 2010, the major sources of the air emission were motor vehicles (82%), power stations (9 %), industrial fuel burning (5%), industrial production processes (3%), domestic and commercial furnaces (0.2%) and open burning at solid waste disposal sites (0.8 %). Mostly, these sources contribute to the air pollution through the combustion of fossil fuels to fulfill nation’s overall energy demand.

1.4 Background

Worldwide energy demand, global environmental concerns, price hiking of petroleum fuels , rapid depletion of fossil fuel along with numerous other factors have stimulated to find alternative fuel sources that will ensure the clean combustion of diesel engines (M Palash et al., 2013; Shahabuddin et al., 2013). Hence, it has become a worldwide agenda to look for clean alternative fuels which are environmentally acceptable, domestically available and technically feasible (Liaquat et al., 2010). According to the Energy Policy Act of 1992 (EPACT, US), natural gas, ethanol, methanol, biodiesel, and electricity – these are the main potential alternative fuels that can decrease global warming, consumption of fossil fuels and exhaust emissions (Jia et al., 2005). As biodiesel is environment friendly and also posseses similar operation properties as diesel fuels it is one best choices amongst the available alternative fuels. If biodiesel is used in internal combustion engines, it can play a massive role in reducing fossil fuel demand, as well as fossil fuel's adverse effect on environment and human health (Mallikappa et al., 2012; Ng et al., 2012; Tan et al., 2012).

Biodiesel, is known as fatty acid methyl ester, is produced from animal fats or vegetable oils by using transesterification process in the absence or presence of any catalyst. If vegetable oils are used directly in engine, it may cause various engine problems such as carbon deposits on both piston and head of engine, injectors coking and also excessive engine wear (Srivastava and Prasad, 2000). For these reasons, vegetable oils must be refined to turn into the quality fuel. These problems can be overcome by following four methods: pyrolysis, dilution with hydrocarbons blending, Micro-emulsion, and transesterification (Demirbas and Demirbas, 2007; Demirbas, 2008, Balat and Balat, 2010; Chauhan et al., 2010; Lin et al., 2011). The process of thermal fragmentation of the organic substances can be classified in two conditions: absence of oxygen and presence of a catalyst is known as Pyrolysis. This process is an effective, waste less, simple and pollution free process (Singh and Singh, 2010). The process which is used to reduce the viscosity of the vegetable oils and also to improve the performance of the engine is known as dilution process. In this process, there is no need of chemical reaction (Balat and Balat, 2010). Micro-emulsion is defined as a colloidal equilibrium dispersion of optically isotropic fluid microstructure with dimensions generally ranging from 1–150 nm and developed impulsively from two typically immiscible liquids and one and more ionic or more ionic amphiphiles. In transesterification process, a chemical reaction is observed between vegetable oil and alcohol in the presence of a catalyst. The resultant biodiesel is biodegradable, non-explosive, renewable, non-flammable, non-toxic and also environment friendly (Lee et al., 2013). The major advantages of biodiesel are it can be blended with diesel fuel at any proportion and there is no need of any kind of engine modification needed to use these blends in the engine (How et al., 2012; Shahabuddin M et al., 2012). Furthermore, biodiesel contains no sulphur and also produces less harmful emission to the environment compared to diesel fuel. Worldwide, there are more than 350 prospective oil-bearing crops, among which *Jatropha curcas*, rapeseed, soybean, palm, sunflower, safflower, cottonseed and peanut oils are regarded as potential alternative feedstocks (Demirbas, 2007; Parawira, 2010; Atadashi et al., 2012). On the other hand, some other non-edible oils such as *Calophyllum inophyllum, Moringa oleifera, Sterculia foetida, Madhuca indica (Mahua), Croton megalocarpus and Pongamia pinnata* etc. are also gaining popularity all over the world. The specification and technical regulation of biodiesel are set by USA as ASTM 6751- 02 or by the European Union as EN 14214.

1.5 Research Objectives

The main objectives of this investigation are:

1. To produce biodiesel from crude edible (Palm) and non-edible (*Jatropha curcas and Moringa oleifera*) oils
2. To characterize the Palm, *Jatropha curcas and Moringa oleifera* oil biodiesel.
3. To study the effect of blending on physico-chemical properties of Palm, *Jatropha curcas and Moringa oleifera* biodiesel.
4. To study the performance and emission characteristics of Palm, *Jatropha curcas and Moringa oleifera* biodiesel blended fuel in a multi cylinder diesel engine.

1.6 Scope of the Work

This study explores the potentiality of available edible and non-edible feedstocks in Malaysia from which biodiesel can be produced. At present, in Malaysia, palm oil is the main crop for biodiesel. Malaysian Government has agreed to use 40% (~6 million tonnes) of palm oil production (15.8 million tonnes) to produce biodiesel. Recently, Jatropha curcas has drawn the attention of the Malaysian Government. They have planned to build a demonstrative project on cultivation of Jatropha curcas to establish the economic feasibility study of the crop for biodiesel production. As Malaysia has sufficient area of land and possesses good climatic condition, it is conducive to cultivate Jatropha; this feedstock can be the best candidate for future biodiesel production.

On the other hand, *Moringa oleifera* have native distribution in Malaysia. The aim of this study is to produce biodiesel from palm, *Jatropha curcas* and *Moringa oleifera* oil as a promising biodiesel feedstock for Malaysia. This was followed by characterizing the fuel properties of produced palm, *Jatropha curcas* and *Moringa oleifera* biodiesel and their blends with diesel. Finally, engine performance and emission characteristics of palm, *Jatropha curcas* and *Moringa oleifera* biodiesel blends (B5 to B20) have been conducted in an unmodified diesel engine and compared with diesel fuel. Data from all of the tests includes crude oil properties, biodiesel production, biodiesel properties, blending effect on fuel properties, engine performance and emission analysis will be correlated and a conclusion will be made based on the all findings.

1.7 Organization of Dissertation

This dissertation is made up of five chapters. The chapters are organized as follows:

Chapter 1 provides a brief introduction or overview of the research topic. It starts with giving an introduction to global energy scenario; Malaysian energy scenario, followed by a background of the study that shows the potential of biodiesel as a renewable energy sources and finally the objectives and scope of the study.

Chapter 2 provides a literature review for the objective based study. It starts with giving a brief discussion about the diesel engine combustion followed by historical background of biodiesel evolution, the sources of biodiesel, production of biodiesel, standards & properties of biodiesel, advantages & disadvantages of biodiesel. The next part comprehensively discusses the impact of biodiesel on engine performance & emission characteristics.

Chapter 3 explains in detail the research methodology and design of experiments. Besides methods which were applied to test the feedstocks' properties, blending effect on fuel properties, blending, engine performance and emission etc. are explained in brief in this chapter.

Chapter 4 is dedicated to present all the results that have been obtained from the experimental tests and analysis. Moreover, the findings of the study followed by a detailed discussion and analysis of all results presented along with comparing them with the existing results presented in the literature.

Chapter 5 provides a summary of the key findings in the light of the research and puts some recommendations for the future studies.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

Quite a significant number of selective literatures have been reviewed in order to critically compare the feasibilities of these target feedstocks (i.e. Palm, *Jatropha curcas and Moringa oleifera*) with other popular biodiesel feedstocks like sunflower, rapeseed, pongamia, Calophyllum inophyllum in different parameters such oil properties, production process, biodiesel properties and standards, engine performance and emission. On selecting references, only highly rated journals with scientific references, Society of Automotive Engineers (SAE) technical notes are taken and some information are gathered from reports from renowned organization like International Energy Agency (IEA), Malaysian Palm Oil Board (MPOB), National Energy Board (NEB), National Institute of Standards and Technology (NIST). The experimental results as well as reason behind of these results are analyzed to find the jest.

2.1 Impact of Diesel Engine Emission on Environment and Human Health

The emissions which are produced due to combustion of petroleum derived fuel have an adverse effect on environment and human health. It is reported by the united nation intergovernmental panel that global warming is increasing due to the greenhouse gas emission including methane, nitrogen oxides and carbon dioxides. Liaquat et al. (2010) reported that if the average global temperature is increased by more than 2° C, many people about hundreds of millions of people will lose their lives. Carbon monoxide (CO), hydrocarbon (HC) and formaldehyde (HCHO), Oxides of nitrogen (NO_x), particulate matter (PM) and organic gases other than methane (Non-Methane Organic Gases, i.e. NMOG) which are emitted from internal combustion engine has been identified as harmful to the human health and environment degradation. Table 2.1 shows the impact of exhaust emissions on human health.

Table 2.1: Impact of Diesel Engine Emission on Human Health

Exhaust Emissions	**Impact on Health**	**References**
PM	Lung cancer and cardiopulmonary deaths	(Zhang 2010)
NO_x	Irritate the lungs and cause oedema, bronchitis and pneumonia; and result in increased sensitivity to dust and pollen in asthmatics	(Faiz 1990)
CO	Its affects fetal growth in pregnant women and tissue development of young children. It has a synergistic action with other pollutants to promote morbidity in people with respiratory or circulatory problems.	(Faiz 1990)
HC	Eye irritation, coughing and sneezing, drowsiness and symptoms akin to drunkenness. Some hydrocarbons have a close affinity for diesel particulates and may contribute to lung disease.	(Faiz 1990)
PAHs	Eye and nose irritation, coughing, nausea and shortness of breath	(Okona-Mensah 2005)
Formaldehyde	Eye and nose irritation, coughing, nausea and shortness of breath	(Onursal 1997)

2.2 Development of Biodiesel in Malaysia

In Malaysia, the production of biodiesel per annum upturned from 1.1 thousand barrel per day in 2006 to 5.7 thousand barrel per day in 2009 which shows an average increase of 26.6% annually (USEIA, 2010). The government of Malaysia had observed the necessity of evolving alternative energy resources particularly on biodiesel in the long term since 1980s. The country is elevated as one of the pioneers in palm biodiesel industry because it produces and exports largest amount of palm oil in all over the world. The palm biodiesel were fortified as an alternative fuel in the Malaysian transport sector, for embracing more renewable sources and getting rise of dependency on fossil fuels. From this time onward, biodiesel production in Malaysia was seen to grow promptly. In 2006, Malaysian government initiated the National Biofuel Policy to boost up the production and consumption of biodiesels. The country also professed a pledge to keep apart six million tons of crude palm oil to enhance the biodiesel production and make the policy fruitful. However, because of introducing of Envo diesel at late' 2006, biodiesel status again solidified as a renewable energy source (Chin, 2011). Nevertheless the country turned back to the inventive mandate of utilizing B5 blend. The execution of B5 mandate was being delayed till the middle of 2011 and it is also limited to the Central Region of Malaysia (Dompok, 2010). A satisfactory status has been achieved by Malaysia in the proper truck to use biomass as a renewable energy source. This t can entertain as a model to the countries in the world having immense biomass feedstock's (Ayob et al., 1998). Presently, Malaysia owns 25 biodiesel plants with total production capacity of 2.6 million tons. Most of these plants are placed in Peninsula Malaysia .

2.3 Sources (Feedstocks) of Biodiesel

More than 350 oil-bearing crops are recognized universally as potential sources for production of biodiesel. The comprehensive variety of prevailing feedstocks for biodiesel production is a major vital advantage. As per existing literature, feedstock acquisition presently considers more than 75% of biodiesel production costs as represented in Figure 2.1. Generally, the biodiesel feedstock's can be distributed into four major categories (Silitonga et al., 2011) such as

1. Edible vegetable oil: canola, soybean, peanut, sunflower, palm and coconut oil.

2. Non-edible vegetable oil: *Jatropha curcas*, *Calophyllum inophyllum*, *Moringa Oleifera* and *croton megalocarpus*.

3. Waste or recycled oil.

4. Animal fats: chicken fat, pork lard, beef tallow and poultry fat

The main feedstock for biodiesel production in Malaysia is Palm oil. The preliminary assessment for physical and chemical characteristics of edible and non-edible feedstocks is of utmost importance to judge their feasibility for imminent biodiesel production. A few physical and chemical properties of edible and non-edible oil feedstocks are found in the study of (Atabani et al., 2013) and (Sanford et al., 2011).

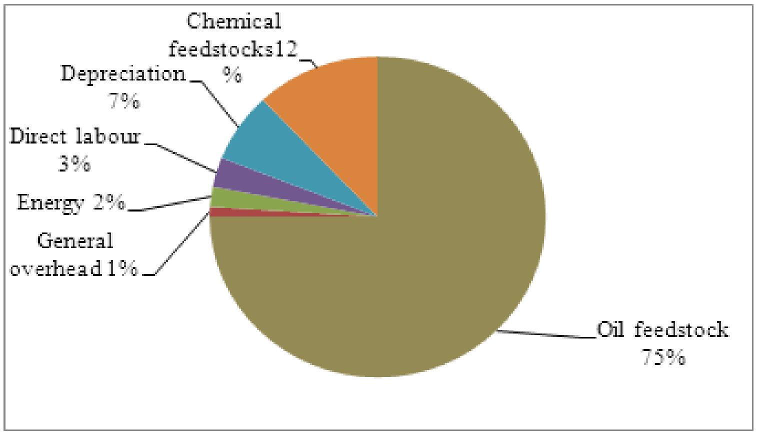


Figure 2.1: General Cost Breakdown for Biodiesel Production

2.4 Production of Biodiesel

Currently, there are number of well-established methods which can be used to produce biodiesel fuel. In order to use as engine fuel, viscosity of crude oils needs to be reduced. This modification can be achieved through several procedures to ensure production of better quality biodiesel. These four primary ways viz. blending of crude oils, thermal cracking, micro emulsions, and transesterification- can be used to achieve the desired modification (Jain & Sharma, 2010; Leung et al., 2010). As vegetable oils have low volatility, high viscosity, and polyunsaturated characteristics, they cannot be directly applied in diesel engines (Srivastava and Prasad, 2000). There is a need of refinement to turn those vegetable oils into quality fuel. Four distinct methods; pyrolysis, dilution with hydrocarbons blending, Micro-emulsion, and transesterification can overcome the constraint well (Demirbas and Demirbas, 2007; Demirbas, 2008; Balat and Balat, 2010; Chauhan et al., 2010; Lin et al., 2011).

2.4.1 Pyrolysis

In pyrolysis process, in the absence of oxygen, one substance is converted into another with help of catalyst or by means of heat. The vegetable oils, natural fatty acids, animal fats, as well as methyl ester of fatty acids can be used for pyrolysis. Pyrolysis process is simple, effective, pollution free and waste less (Singh and Singh, 2010).

2.4.2 Blending of Crude Oils or Dilution

To resolve the problem of high viscosity of crude vegetable oils, they can be blended directly or diluted with diesel fuel to increase the viscosity for using in compression ignition engines. In 1980, Caterpillar Brazil maintained total power using a 10% mixture of vegetable oil without altering the engines. Also, a blend of 20% vegetable oil with 80% diesel fuel was also successfully reported by (Singh and Singh, 2010). Dilution is a process in which without any chemical reaction reduction of viscosity of the vegetable oils as well as improvement in engine performance can be achieved (Balat and Balat, 2010).

2.4.3 Micro-Emulsification

Micro-emulsion is demarcated as a colloidal equilibrium dispersion of optically isotropic fluid microstructure usually ranging from 1–150 nm dimensions formed instinctively from two normally immiscible liquids together with one or ionic amphiphiles (Moser, 2009). The micro-emulsification process can be used to lessen the viscosity of vegetable oil. Micro emulsions are clear and stable isotropic fluids containing three types of components such as oil phase, aqueous phase and surfactant. A complex mixture of olefins and hydrocarbons are the constituent of the oil phase whereas salts are constituents of the aqueous phase. Aqua phase also may contain other ingredients. Spray characteristics can be improved by this ternary phase through quick-tempered vaporization of low boiling components in micelles. Limitation of maximum viscosity can be met by all micro-emulsions using butanol, hexanol and octanol (Jain and Sharma, 2010).

2.4.4 Transesterification

Adopting the transesterification process, the triglyceride can nicely be converted into monoester. In this process, when a catalyst is existent, three consecutive reversible chemical reactions, involving triglycerides and alcohol, produce esters and glycerol. The inclusive transesterification reaction can be deliberated by three consecutive and reversible equations (2.1-2.3)

Triglyceride (TG) + ROH ↔ Diglycerides (DG) + RCOOR1……………………….. (2.1)

Diglycerides (DG) + ROH ↔ Monoglyceride (MG) + RCOOR2…………………… (2.2)

Monoglyceride (MG) + ROH ↔ Glycerol + RCOOR3……………………………… (2.3)

To reduce the reaction time and to enhance reaction rate usually a catalyst is chosen. There are three common kinds of catalysts in the ester reaction: lipase catalysts, acid catalysts, and alkali catalysts. Each catalyst has its own advantages and disadvantages in the whole reaction process. As transesterification process is reversible, in order to shift equilibrium towards product side excess alcohol is used. Hence ester and crude glycerol are produced from a fruitful transesterification reaction produces. In this process, glycerin recovery shows its vital importance because of its frequent applications in daily products (Ramadhas et al., 2005a). The transesterification reaction can be catalyzed by alkalis, acids or enzymes (Demirbas, 2005).

Amongst the four techniques, transesterification is the most promising technique to resolve the higher viscosity issues. At present, transesterification is widely available technique for industrialized biodiesel production due to its higher conversion efficiency and lower cost (Balat and Balat, 2010; Jain and Sharma, 2010; Parawira, 2010). Details classification of transesterification process has shown in Figure 2.2.

2.5 Factors Affecting the Transesterification Process

The transesterification reaction is affected by several parameters reliant on the reaction environments. If the parameters are not optimized, the reaction may either be incomplete or the yield is lessened to a momentous amount. The most imperative parameters affecting the transesterification process are revealed as below:

- Moisture, FFA and water content.
- Kind of alcohol
- Molar ratio applied
- Sort and deliberation of catalysts.
- Reaction temperature
- Reaction time.
- Speed and method of stirring.
- Purification process.
- Mixing strength.
- Influence of using organic co-solvents.

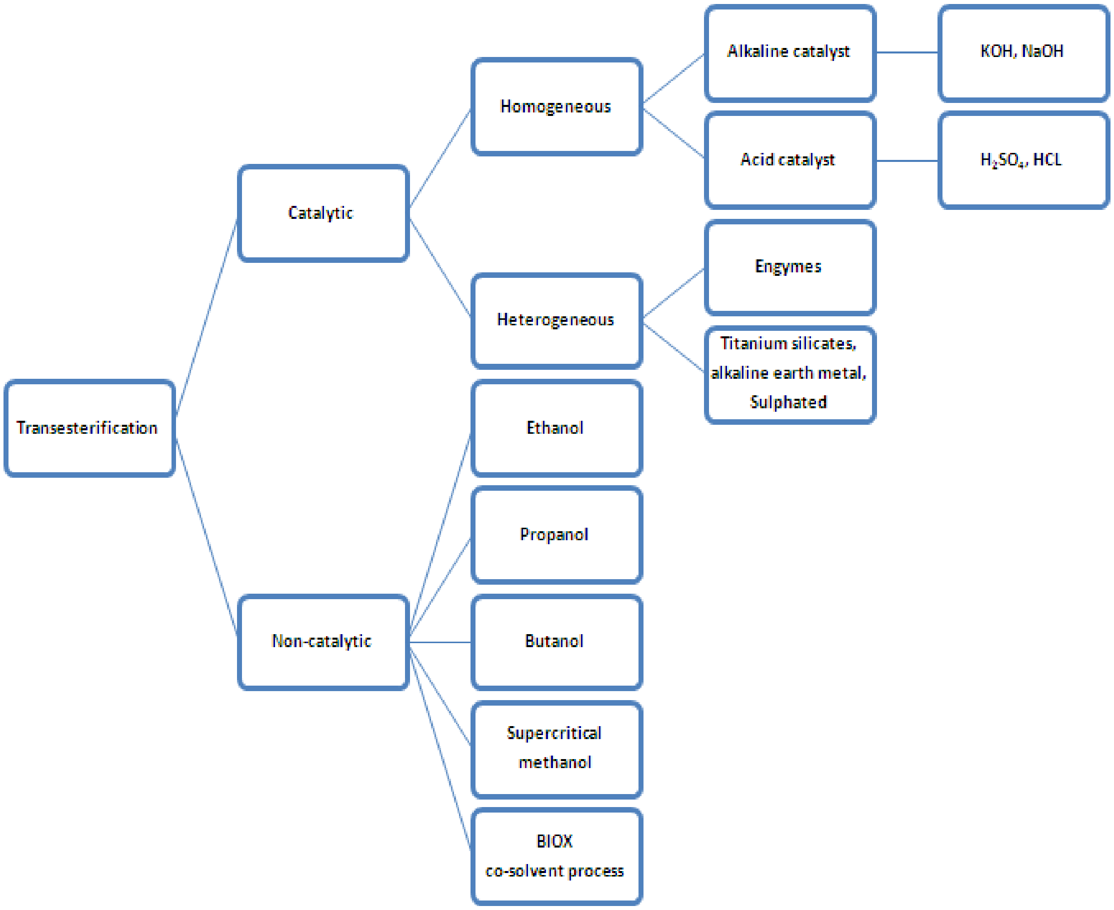


Figure 2.2: Classification of Transesterification Process

2.6 Standards and Properties of Biodiesel

Quality standards for producing, storing and marketing of biofuel are being technologically advanced and employed worldwide in order to maintain the end product quality and also to ensure consumers' confidence. Austria was the first nation in the world which defined and approved the standards for rapeseed oil methyl esters as a diesel fuel. At present the US and the EU standards are the most referred standards followed by standards from other biofuel producing countries. The US and EU standards are shown in Table 2.2. The compositions of fatty acid in different biodiesel fuels are presented in Table 2.3.

Table 2.2: ASTM And EN Specifications for Biodiesel (B100) (Silitonga et al. 2011)

Properties	**ASTM D 6751**		**EN 14214**	
	Limit	Method	Limit	Method
Density	870–890 kg/m^3	ASTM D4052-91	860–900 kg/m^3	EN ISO 3675, EN ISO 12185
Flash point	130 ◦C minimum	ASTM D93	>101 ◦C (minimum)	EN ISO 3679
Viscosity @ 40 ◦C	1.9–6.0 mm^2/s	ASTM D445	3.5–5.0 mm^2/s	EN ISO 3140
Cloud point	Report to customer	ASTM D2500	Based on national specification	EN ISO 23015
Copper strip corrosion	Class 3 maximum	ASTM D130	Class 1 rating	EN ISO 2160
Cetane number	47 (minimum)	ASTM D613	51(minimum)	EN ISO 5165
Water content and sediment	0.050 (%v) maximum	ASTM D2709	500 mg/kg (maximum)	EN ISO 12937
Acid number	0.50 mg KOH/g maximum	ASTM D664	0.50 mg KOH/g (maximum)	EN 14104
Free glycerin	0.02% (m/m) maximum	ASTM D6584	0.02% (m/m) (maximum)	EN 1405/14016
Total glycerol	0.24% (m/m) maximum	ASTM D6548	0.25% (m/m)	EN 14105
Methanol content	0.20% (m/m) maximum	EN 14110	0.20% (m/m) (maximum)	EN 14110
Distillation temperature	360 ◦C	ASTM D1160	--	--
Oxidation stability	3 h minimum	EN ISO 14112	6 h (minimum)	EN ISO 14112
Carbon Residue	0.05 maximum wt.%	ASTM D 4530	0.30%(m/m) (maximum)	EN OSO 10370
Iodine number	--	--	120 g iod/100 g (maximum)	EN 14111

The properties of biodiesel are designated by physicochemical properties such as density, viscosity, oxidation stability (OS), flash point (FP), cetane number (CN), Cloud point (CP), Pour point (PP), Cold filter plugging point (CFPP) and lubricity etc. Foremost characteristics of biodiesel are discussed as follows:

Table 2.3: Fatty Acid Compositions of Different Biodiesel Fuel

FAME	C12:0	C14:0	C 16:0	C18:0	C 18:1	C18:2	C18:3	C20:0	C22:0	C24:0
Rapeseed oil ME	-	-	6	2.4	59.3	28.6	2.7	0.9	-	-
Sunflower oil ME	-	-	8	4.7	28.9	56.5	0.7	-	1.2	-
Palm oil ME	-	1.3	44.7	5.4	37.2	10.8	-	0.5	-	-
Soy oil ME	-	-	13	4.9	23.9	49.6	7.3	0.5	0.8	-
Milk thistle oil ME	-	-	10	6.2	22.7	50.7	1.2	4.1	3.9	1.2
Linseed oil ME	-	-	6.1	4.6	17.5	15.9	55.9	-	-	-
Camelina oil ME	-	-	6.7	3	14.3	18.2	48.4	2.3	0.7	6.5
Jatropha oil ME	-	-	17.7	7.9	37.8	36.6		-	-	-
Canola oil ME	-	-	5.6	2.4	63.6	23.4	3.2	1	0.8	-
Animal Fat ME	-	2.3	29.8	17.1	37.7	11.5	1.7	-	-	-
Lard ME	0.4	2.3	29.6	20	33.2	13.1	1.5		-	-

2.7 Impact of Biodiesel from Various Feedstocks on Engine Performance and Emissions Characteristics

2.7.1 Rapeseed

Ekrem (2010) investigated the performance, emission and combustion characteristics a diesel engine using pure rapeseed biodiesel and 5%, 20% and 70% biodiesel blends at full load. The results show that there are no noticeable differences in the measured engine power output between diesel and B5 fuels. However, the measured engine power for other blends is lower than that of the diesel fuel. Moreover, the use of biodiesel produces lower CO and smoke opacity and higher BSFC, higher exhaust gas temperatures and NO_x emissions compared to diesel fuel. It was found that B20 gives the best brake thermal efficiency of engine. The test results indicated that the only low concentration blends in terms of performance efficiency and environmentally friendly emissions could be recognized as the potential candidates to be certificated for full scale usage in unmodified diesel engines.

2.7.2 Soybean

Qi et al. (2010) studied the combustion and performance characteristics of a direct injection engine fueled with biodiesel from soybean oil and its different blend (B0, B30, B50, B80, B100). The test result showed a small increase in BSFC for biodiesel and its blends due to the lower heating value of biodiesel. The BTE of biodiesel and its blends are slightly lower than that of diesel at low engine loads keeping the same trend to the higher engine load. The significant improvement in reduction of carbon monoxide (CO) and smoke were found for biodiesel and its blends at high engine loads. HC emissions of biodiesel and its blends have little difference from those of diesel fuel. Nitrogen oxides (NO_x) were slightly higher for biodiesel and its blends. This is because of the increases the combustion chamber temperature due to higher oxygen content in biodiesel. The authors concluded that the excess oxygen contents of biodiesel play a key role in engine performance and biodiesel is proved to be a potential fuel for complete or partially replacement of diesel fuel.

2.7.3 Mahua (*Madhuca Indica*)

Saravanan et al. (2010) investigated the performance and emission of a diesel engine fuelled with *Madhuca indica* biodiesel. Experiments were conducted on a single cylinder, four strokes; air cooled, direct injection, compression ignition engine using Mahua oil methyl ester and diesel as fuel. The result showed that at full load, the power loss was around 13% along with 20% increase in fuel consumption with Mahua oil methyl ester due to the lower heating value and higher viscosity of biodiesel fuel. Emissions such as carbon monoxide, hydrocarbons were lesser for Mahua ester compared to diesel by 26% and 20%

respectively due to the higher oxygen contents which promoted combustion. Oxides of nitrogen were lesser by 4% for the ester compared to diesel due to the lower in cylinder temperature. Besides, smoke intensity was reduced by 15% for MOME at full load. It was also observed that the exhaust gas temperature lowered for MOME blended fuel combustion compared to that of diesel.

2.7.4 Jojoba

Saleh (2009) studied the performance and exhaust emissions of a two-cylinder, naturally aspirated, four-stroke direct injection diesel engine operating with diesel and Jojoba methyl ester (JME). This was followed by studying the effect of exhaust gas recirculation (EGR). The result showed that the engine power and brake thermal efficiency with JME are slightly higher than the diesel. The BSFC with JME is lower (8.2-9.8%) than that of diesel. Author also found that JME also give higher concentration of NO_x of 14% at 1600 rpm and 16% at 1200 rpm. At lower engine speed JME produce higher HC and CO emissions. At high speed, there is no appreciable difference between HC concentration with JME and diesel fuel while CO of JME is lower than diesel. The results also showed that when the EGR rate is increased, the NO_x emissions decreased. However, CO and HC emissions increased. The optimum EGR level is 5-15% for all engine speeds and loads and that may be favorable in a trade-off between HC, CO and NO_x emissions with little economy penalty.

2.7.5 Neem

Sharma et al. (2009) studied the performance and emissions of a direct injection diesel engine fueled by Neem-diesel blend. They reported that neem biodiesel gives slightly lower brake thermal efficiency (BTE) and higher brake specific fuel consumption (BSFC) than diesel at all loads. A significant reduction in the NO_x, smoke density, CO and unburned hydrocarbon (UHC) emissions with compare to diesel fuel was observed.

2.7.6 Pistacia Chinensis Bunge

Zhihao et al. (2011) studied the emission characteristics of a diesel engine fuelled with Pistacia Chinensis Bunge Seed biodiesel blend. The result showed that CO, HC and exhaust smoke emissions decrease with the increase of the proportions of biodiesel in the blends due to the higher oxygen contents and absence of sulphur in the blend. The NO_x emissions are reduced as the engine operating with B10 and B20, but slightly increased with B30 due to the higher oxygen contents which increases the in cylinder temperature.

2.7.7 Beef Tallow

Selvam and Vadivel (2012) studied the performance and emission of a diesel engine using beef tallow biodiesel (B100) and its blends (B5, B25, B50, B75) with diesel at different load condition and constant speed of 1500 rpm. The test result indicates that blended fuels give a slight decrease in BTE and increase in BSFC compared to that of diesel fuel due to the higher density and lower heating value of biodiesel fuel. The emission analysis shows a radical reduction in carbon monoxide (CO), unburned hydrocarbon (UHC) and smoke density for all biodiesel blended fuel due to the higher oxygen contents in biodiesel fuel. The maximum reduction in CO, HC and smoke emission with neat biodiesel are 24.7%, 32.5% and 63% respectively. However, in the case of oxides of nitrogen, there is a slight increase for all the blended fuels and with neat biodiesel (6.35%) compared to diesel fuel. The authors concluded that methyl esters of beef tallow and its blends with diesel fuel can be used as an alternative fuel for diesel in direct injection diesel engines without any significant engine modification.

2.7.8 Palm

Karavalakis et al. (2009) investigated regulated, unregulated exhaust emissions and fuel consumption of diesel fuel and palm based biodiesel blends at proportions of 5%, 20% and 40% (v/v). A Euro 3 compliant light duty vehicle was tested on a chassis dynamometer over the new European driving cycle (NEDC) and the non-legislated Athens driving cycle (ADC). The experimental results showed that the addition of biodiesel increased NOx emissions. This increase was more significant with the use of B20 over both cycles (13.7% and 23.2% over the NEDC and ADC, respectively). Biodiesel addition resulted to increases in CO emissions with the highest increase being 11.78% for B20 over NEDC and 11.62% for B40 over ADC. HC emissions increased with biodiesel over the NEDC, while over the ADC the addition of biodiesel led to reductions with the highest being with the use of B40 (about 26.47%). The same observation holds for PM emissions. Over the ADC the most beneficial reduction was in the order of 50% for the B40. CO_2 emissions and fuel consumption followed similar patterns. B20 led to increases up to 6.16% and 2.94% in fuel consumption over NEDC and ADC, respectively. Some PAH compounds demonstrated an increase with biodiesel, while nitro-PAHs decreased with most of them being almost undetectable. Most carbonyl emissions decreased with biodiesel.

Kalam et al. (2011) studied emission and performance characteristics of an indirect ignition diesel engine fuelled with 5% palm (P5) and 5% coconut oil (C5) with diesel fuel at constant 85% throttle position. The results show that there are reductions in brake power of 1.2% and 0.7% for P5 and C5 respectively compared with B_0. This reduction is mainly owed to their respective lower heating values. Compared with B_0, P_5 increases exhaust gas temperature by 1.42% and C5 decreases it by 1.58%. However, both C_5 and P_5 reduce CO by 7.3% and 21% respectively and HC by 23% and 17% respectively. However, C5 reduces 1% and P5 increases 2% of NO_x emission. It was noted that P5 produces higher CO_2 than C5 and B0 fuels. This is mainly the effect of high unsaturated fatty acid in palm oil.

Leevijit and Prateepchaikul (2011) studied the performance and emission characteristics of IDI-turbo automobile diesel engine operated using degummed, deacidified mixed crude palm oil-diesel blends at various loads and speeds. The test result showed that all blends produce the same maximum brake torque and power. A higher blending portion results in a little higher brake specific fuel consumption (+4.3% to +7.6%), a slightly lower brake thermal efficiency (-3.0% to -5.2%), a slightly lower exhaust gas temperature (2.7% to 3.4%), and a significantly lower amount of black smoke (-30% to -45%). The CO emission of the 20 vol. % blend is significantly lower (-70%), and the NO_x emissions of all blends are little higher. The authors concluded that blending of degummed, deacidified palm oil in diesel up to 40 vol. % has been found to be satisfactory for short-term usage in the IDI-turbo automotive diesel engine.

Ng et al. (2012) studied the engine performance using neat palm oil methyl ester, B50 and neat diesel (B0) at different speeds and load conditions. The result showed that SFC for palm oil methyl ester is higher than diesel fuel due to lower energy contents. They also found that neat palm oil methyl ester (B100) reduces tailpipe NO, UHC and smoke opacity by 5.0%, 26.2% and 66.7%, respectively due to improved combustion, higher cetane number and oxidation of soot. However, it was found that PME content in the fuel blend did not significantly affect tailpipe CO emission, with only a maximum 0.89% reduction achieved with the B50 blend. The authors concluded that despite the shortcoming of PME in its higher specific fuel consumption, its overall reduction of regulated tailpipe emissions makes PME green technically viable alternative to fossil diesel in both neat and blended forms for use in light-duty diesel engines.

2.7.9 *Jatropha Curcas*

Sahoo et al. (2009) studied the performance and emission characteristics of Jatropha based biodiesel as fuel in a tractor engine. During the part throttle performance test they found best brake specific fuel consumption (BSFC) improvement with jatropha biodiesel blend. They also found the significant reduction in smoke, hydrocarbon (HC), particulate matter (PM) with biodiesel and their blend but slightly increase of oxides of nitrogen (NOx) and carbon monoxides (CO) emissions. The reason of increasing NOx is the presence of oxygen in biodiesel which causes an increase in combustion gas temperature resulting in increasing NOx emission.

Huang et al. (2010) studied the emission characteristic of a diesel engine using jatropha biodiesel compared with diesel fuel. They reported that the performance and thermal efficiency of the engine run by biodiesel is comparable with that of diesel fuel. Emissions are reduced to some extent when using the biodiesels. CO emissions are reduced 20-25% when the engine runs at engine high loads and also 17-23% HC emissions are reduced compared to diesel fuel. NOx emissions are also reduced at different engine loads. Smoke emissions from the engine fuelled by the biodiesels are lowered significantly than that fuelled by diesel.

Rao (2011) studied the performance and emission analysis of pure Jatropha biodiesel and preheated jatropha biodiesel fuel in a single cylinder diesel engine and compared with that of diesel fuel. The results showed that the biodiesel performance and emissions are lower than that of diesel fuel. However, the NOx emission of Jatropha biodiesel is more than that of diesel fuel. These high NOx emissions are due to the presence of unsaturated fatty acids and the advanced injection caused by the higher bulk modulus (or density) of Jatropha biodiesel.

Chauhan et al. (2012) evaluated the performance and exhaust emissions using 5%, 10%, 20% and 30% Jatropha biodiesel blends with diesel fuel on an unmodified diesel engine. The experimental results show that engine performance with biodiesel of Jatropha and its blends were comparable to the performance of diesel fuel. In case of all fuel blends, brake thermal efficiency, HC, CO, CO_2 and smoke density were lower while BSFC and NO_x were higher than that of diesel. The authors concluded that biodiesel derived from Jatropha and its blends could be used in a conventional diesel engine without any modification. However there are various parameters which can be evaluated in future such as the prediction of best blend with respect to the various engine parameters by varying spray time of fuel using common-rail fuel injection.

2.7.10 *Moringa Oleifera*

Rashid et al. (2008) evaluated the Moringa oleifera oil as a potential feedstock for biodiesel production in Pakistan. They produced biodiesel using two-step process including pretreatment and esterification process. They found that the methyl esters (biodiesel) obtained from Moringa oil exhibit a high cetane number of approximately 67, one of the highest found for a biodiesel fuel. Other fuel properties of biodiesel derived from M. oleifera such as cloud point, kinematic viscosity and oxidative stability were also meet biodiesel standards such as ASTM D6751 and EN 14214. Authors concluded that, M. oleifera oil appears to be an acceptable feedstock for biodiesel.

Rajaraman et al. (2009) reported on the performance and emission characteristics of Moringa oil methyl ester and its blend (B20-B100) in a DI diesel engine at various load condition. They reported that, in comparison to diesel fuel *Moringa oleifera* methyl ester blends have lower brake thermal efficiency (BTE) because of having lower heating value, higher viscosity and density than diesel fuel. In case of engine emission *Moringa oleifera* methyl ester blend produce lower HC, CO, PM emission but higher NO_x emission compared to diesel fuel.

Da Silva et al. (2010) studied the characterization and production of biodiesel from Moringa oleifera oil. They collected seeds from the northeast of Brazil, evaluated some properties and chemical composition of the oil, as well any potential application in biodiesel production. They concluded that the material may be used as a fuel in diesel engines, mainly as a mixture to petro diesel.

Kafuku and Mbarawa (2010) evaluated the Moringa oleifera oil from Tanzania as a potential raw material for biodiesel production and identified optimal reaction condition for biodiesel production. Experimental results of their study showed that larger catalyst amounts favor the saponification process while greater methanol amounts hinder the separation of glycerin from methyl esters. Moreover, at optimal catalyst and methanol amounts, there is a correlation between reaction time, temperature and agitation speed. At higher temperatures and agitation speed the reaction takes a shorter time to complete while at lower temperature and agitation speed the reaction needs a longer time to achieve completion. The best combination of an alkali-catalyzed transesterification condition is: a methanol to oil ratio of 30 wt%; 1.0 wt% of KOH; a temperature of 60°C; an agitation speed of 400 rpm and a reaction time of 60 min: with these conditions the optimal MOME yield achieved was 82%. Properties of MOME met minimum requirements of both the

ASTM D6751 and EN 14214 biodiesel standards despite the finding that MOME showed high values of cloud and pour points of 10°C and 3°C respectively.

CHAPTER 3

METHODOLOGY AND EXPERIMENTAL SET UP

3.0 Introduction

Research methodology is a crucial factor to bring in an effective research with accredited results. It can be define in many ways such as procedures, ways, methods and techniques that are applied to incorporate and gather all relevant information for the research.

This chapter explains how the whole research was conducted and shows the methods by which crude oil collection and crude oils characteristics, biodiesel production, fatty acid composition, FT-IR analysis and physical and chemical properties of Palm, *Jatropha curcas* and *Moringa oleifera* biodiesel were conducted according to the ASTM D6351 and EN 14214 standards. The opportunity of biodiesel-diesel blending (10-90% by volume blend) to improve some of the properties of each feedstock was also studied in this research. The properties of biodiesel blends were estimated using the polynomial curve fitting method. Moreover, 13 fuel samples were selected to evaluate their performance in a multi-cylinder diesel engine.

3.1 Structure of Research Methodology

This paper aims to produce biodiesel from various edible and non-edible oils that are readily available in the Malaysia or have native distribution to Malaysia. Figure 3.1 gives a summary of the implemented flow chart of this paper.

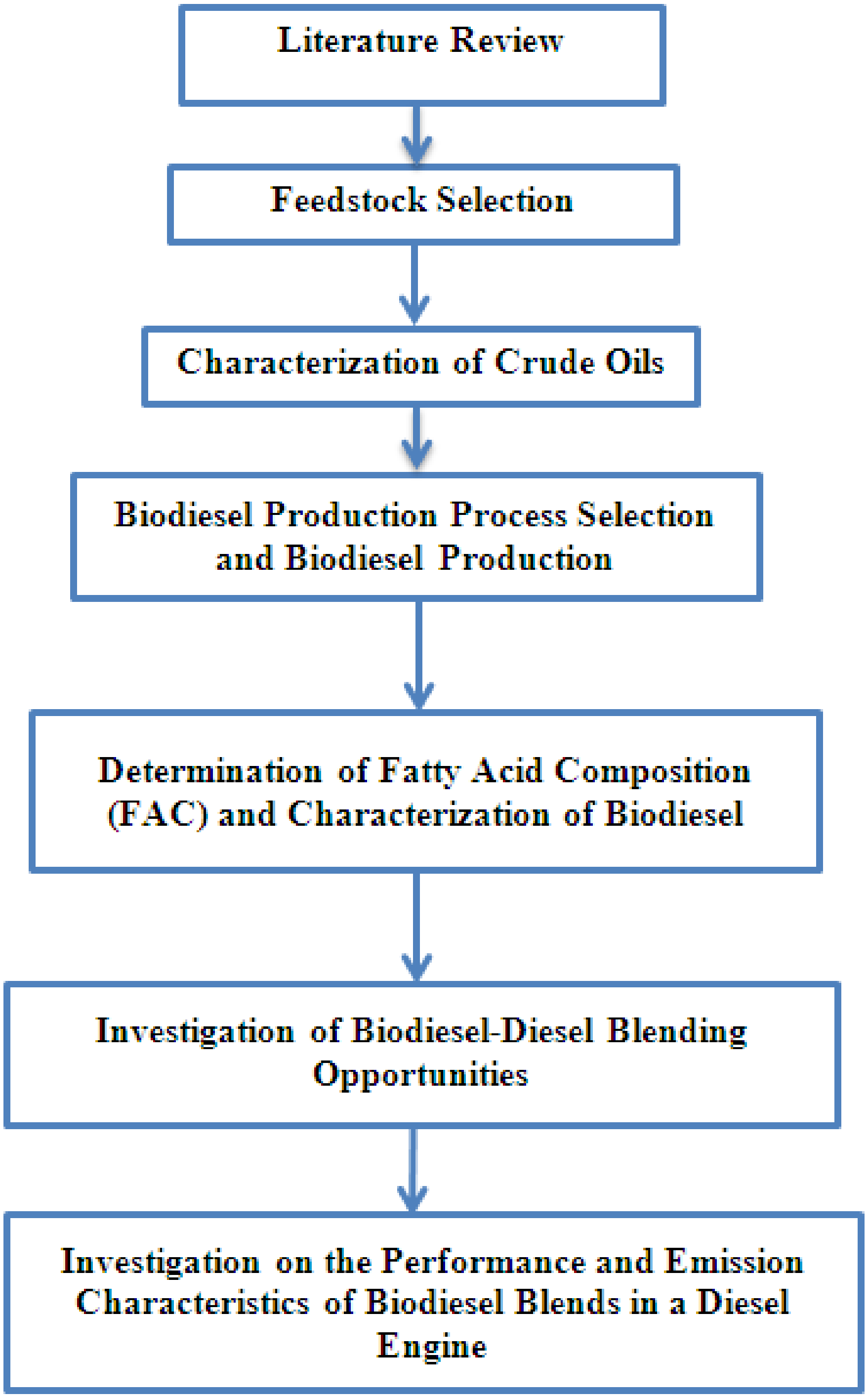


Figure 3.1: Flow Chart of the Research Methodology

3.2 Selection of Biodiesel Feedstocks

In this study biodiesel feedstock was selected on the basis of available sources or has native distribution in Malaysia. So there are three types of biodiesel feedstocks such as Palm, *Jatropha curcas and Moringa oleifera* have been selected. Figure 3.2 shows some pictures of palm, *Moringa oleifera* and *Jatropha curcas*.

(a) Jatropha curcas

(b) Palm

(c) *Moringa oleifera*

Figure 3.2: Pictures of Palm, *Jatropha Curcas* and *Moringa Oleifera* Feedstocks (Atabani et al. 2013)

The reason of choosing these feedstocks is that Malaysia is the world's second largest palm produce country and the production of biodiesel in Malaysia is palm oil based. Recently Malaysian government has taken initiative to introduce *Jatropha curcas* as it non edible feedstocks and doesn't create food versus fuel conflict. *Moringa oleifera* still is not introduced in Malaysia as a biodiesel feedstock but it has a native distribution in Malaysia. The crude oils of *Moringa oleifera* oil was obtained from personal communication and Palm and *Jatropha curcas* were purchased from Forest research Institute, Malaysia (FRIM).

3.3 Biodiesel Production

Free fatty acid (FFA) and acid values are the main identifier of production process. If the crude oil contains higher acid value then two step processes is required because of forming fatty acid salts during the conversion of FFA into FAME (Fatty acid methylester) using alkaline catalyst. The fatty acid salt prevents to separate FAME layer from glycerin.

The acid values of crude Palm, *Jatropha curcas* and *Moringa oleifera* oils were measured to be 3.47, 10.7 and 8.62 mgKOH/g oil respectively. Therefore two step (acid-base catalyst) processes were selected to convert crude Jatropha and *Moringa oleifera* oil into Jatropha and *Moringa oleifera* biodiesel and only transesterification process was selected to convert palm biodiesel. The summary of biodiesel production process is given in Table 3.1. However, production of biodiesel from these crude oils has been conducted as follow:

(a) Pre-treatment process.
(b) Esterification process.
(c) Transesterification process.

(d) Post-treatment process

The apparatus used for biodiesel production was a small scale laboratory reactor consisting of 1L three necked round bottom flask, condenser to recover methanol, thermometer and heating plate equipped with a magnetic stirrer. A separating funnel with a valve at the bottom was used for collection of the final products.

Table 3.1: Summary of Biodiesel Production Process

No	Process parameter	Process specification
01	Process selected	Acid-base catalyst process
02	Reaction temperature	60°C
03	Catalyst used	98% pure sulphuric acid (1%v/v) & 99% pure potassium hydroxides (1% m/m)
04	Alcohol used	Methanol
05	Molar ratio	12:1 for esterification and 6:1 for transesterification
06	Reaction time	3 hours for esterification and 2 hours for transesterification
07	Setting time	15h
08	Stirring speed	600 rpm

3.3.1 Pretreatment Process

In this process, crude Palm, *Jatropha curcas* and *Moringa oleifera* oils were entered in a rotary evaporator and heated to remove moisture for 1 hour at 95°C under vacuum.

3.3.2 Esterification Process

In this process, the molar ratio of methanol to refined *Jatropha curcas* and *Moringa oleifera* oils were maintained at 12:1 (50% v/v). 1% (v/v) of sulphuric acid (H_2SO_4) was added to the pre-heated oils at 60^{o}C for 3 hour under 600 rpm stirring speed in a glass reactor. On completion of this reaction, the products were poured into a separating funnel to separate the excess alcohol, sulphuric acid and impurities presented in the upper layer. The lower layer was separated and entered into a rotary evaporator and heated at 95°C under vacuum conditions for 1 hour to remove methanol and water from the esterified oil.

3.3.3 Transesterification Process

In this process, crude palm oil and esterified *Moringa oleifera* and *Jatropha curcas* oils were reacted with 25% (v/v) of methanol and 1% (m/m) of potassium hydroxide (KOH) and maintained at 60^{o}C for 2 hours and 600 rpm stirring speed. After completion of the reaction, the produced biodiesel was deposited in a separation funnel for 15 hours to separate glycerol from biodiesel. The lower layer which contained impurities and glycerol was drawn off.

3.3.4 Post-Treatment Process

Methyl ester formed in the upper layer from the previous process was washed to remove the entrained impurities and glycerol. In this process, 50% (v/v oil) of distilled water at 60^{o}C was sprayed over the surface of the ester and stirred gently. This process was repeated several times until the pH of the distilled water became neutral. The lower layer was discarded and upper layer was entered into a flask and dried using Na_2SO_4 and then further dried using rotary evaporator to make sure that biodiesel is free from methanol and water.

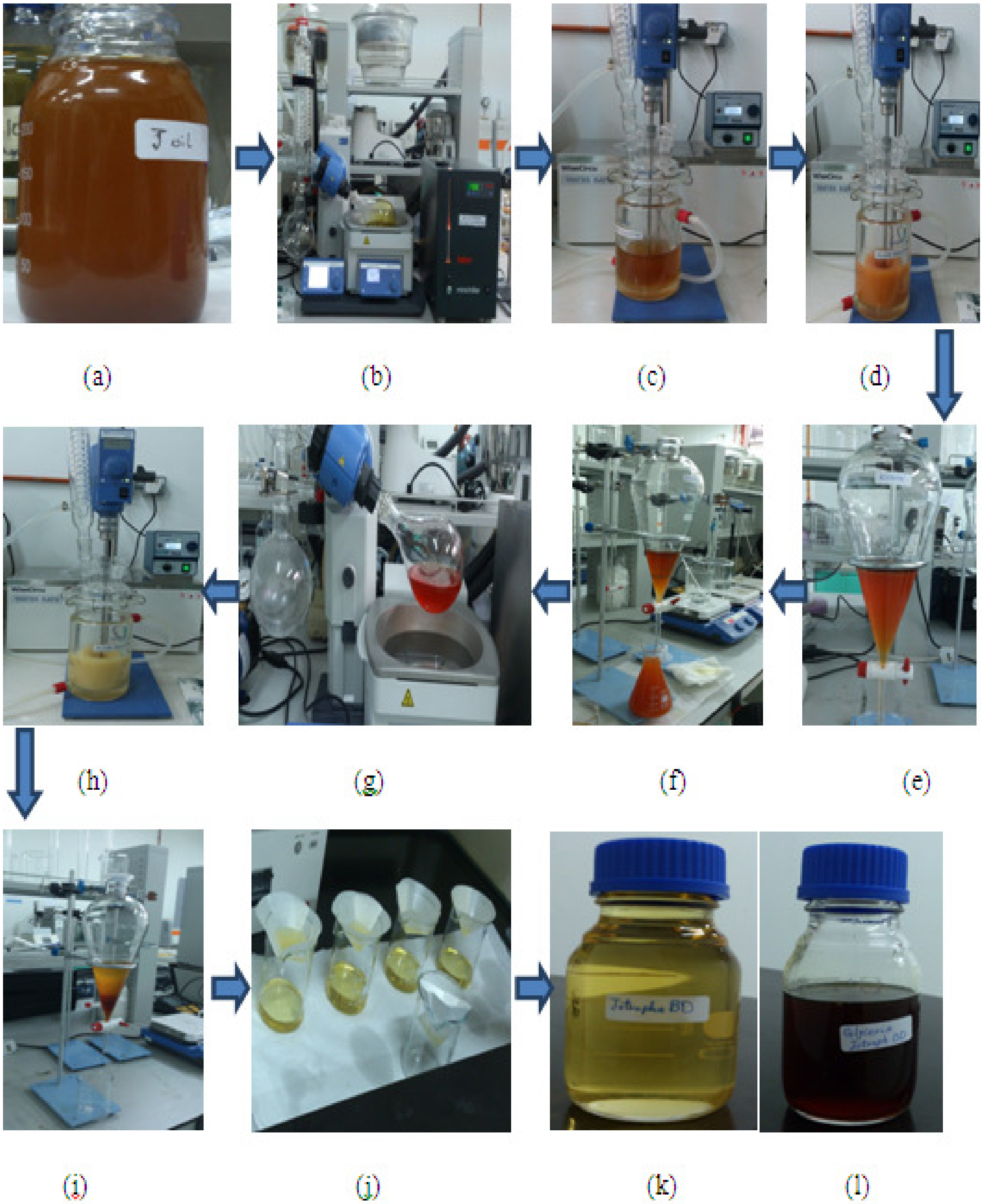


Figure 3.3: Biodiesel Production Process (a) Crude Oil (b) Remove Moisture (c) & (d) Esterification (e & f) Removal of Impurities (g) Removal of Methanol and Water (h) Transesterification (i) Settling (j) Filtering (k & l) Biodiesel & Glycerol respectively

3.4 Determination of Fatty Acid Composition

In this test 0.25g of each sample samples was diluted with 5ml n-heptane. The solution was then entered into GC (GC 7890A, Agilent technologies). Table 3.2 shows the operating condition used to perform this analysis.

Table 3.2: GC Operating Conditions

Property	Specification
Carrier gas	He at 23.878Psi
Linear velocity	44.124cm/s at 100°C
Flow rate	Air = 450mL/min H_2 = 40mL/min He = 20ml/min
Detector temperature	250°C
Column head pressure	23.878Psi
Column dimensions	30m x 0.25mm x 0.25µm
Injector	Type = split and splitless Split ratio 50:1 Injection volume 0.3µL
Temperature Ramp 1	100°C hold for 0 min
Temperature Ramp 2	10°C/min to 250°C hold for 5 min

3.5 FT-IR Analysis

Biodiesel from Palm, *Jatropha curcas* and *Moringa oleifera* oils were characterized by FT-IR, using a Perkin Elmer biodiesel FAME analyzer equipped with the MIR TGS detector in the range 4000-400 cm^{-1} and processed with the computer software program spectrum. The resolution was 4 cm^{-1} and 8 scans.

3.6 Fuel Properties Measuring Procedure and Equipment

The quality of oil is expressed in terms of the fuel properties such as viscosity, density, calorific value, CCR, flash point, pour point, cloud point and cold filter plugging point etc.

The important physical and chemical properties of the crude oils and their methyl esters were tested according to ASTM D6751 standard.

3.6.1 Dynamic Viscosity, Kinematic Viscosity, Density and Viscosity Index Measurement

Density is defined as the ratio of mass to volume and Viscosity is the measure of the flow resistance of a fluid. It provides an estimation of the time required for a given volume of fuel to flow through a calibrated glass capillary tube under gravity. In this study, an Anton Paar automatic viscometer (SVM 3000) was used as shown in Figure 3.4 to measure the dynamic viscosity (mPa.s) and density (kg/cm^3) of the fuel according to ASTM D7042. From this result, the viscometer automatically calculates the kinematic viscosity and delivers measurement results which are equivalent to ISO 3104 or ASTM D445. Biodiesel viscosity was measured at +40°C and 100°C. The viscosity index is an important value, especially in the automotive industry. The viscosity index is calculated from the kinematic viscosity at 40 °C and at 100 °C. The SVM 3000 covers the whole measuring range from less than 1 to 20 000 mm^2/s.

However, to calculate the kinematic viscosity from the dynamic viscosity, density result is required. For this reason, a density measuring cell in SVM 3000 has been given. Both cells are filled in one cycle and the measurements are carried simultaneously. However by using mode settings menu, selection of required standard test can be adapted from 10 predefined standards settings. After switching ON, a self-test and the initializing procedure will be performed by SVM. After that it becomes ready for measurement and will show the first measuring window. During the measurement, current repeat deviation for density and viscosity can be viewed. If the results of the first repetition are within the limits for the viscosity and density, the state changes to ‘RESULT VALID’ and the display will be frozen. If the result is not within the limits, the repeat deviation for viscosity and density will be displayed and one more refill will be required unless it becomes within the limit automatically. Some technical data is given in Table 3.3.

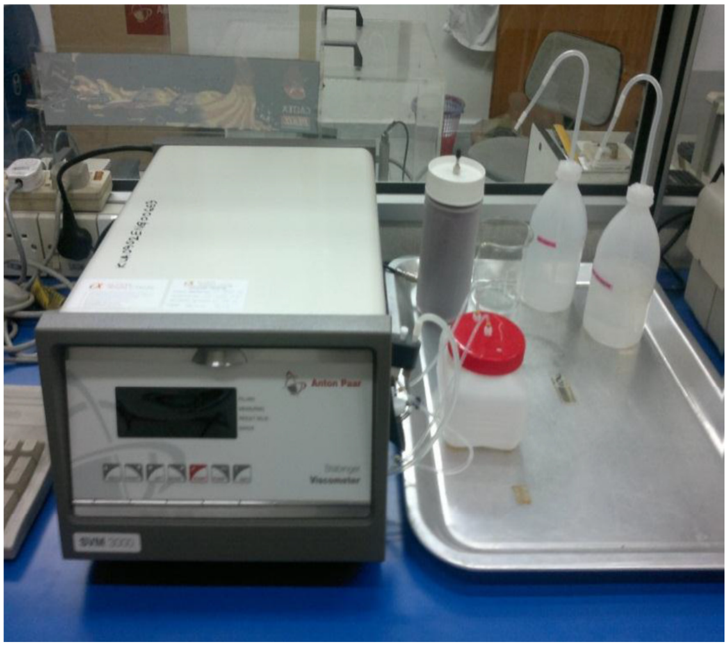


Figure 3.4: Anton Paar (SVM 3000) Viscometer Set Up

Table 3.3: Technical Data for Anton Paar (SVM 3000) Viscometer

Parameter	**Values**
Dynamic viscosity (mPa.s)	0.2-20000
Density (g/cm^3)	0.65-3
Temperature (°C)	15-105
Repeat deviation of viscosity	0.1%
Repeat deviation of density (g/cm^3)	0.0001
Space requirements L×W×H(mm)	440×315×220

3.6.2 Flash Point Measurement

This is the minimum temperature of the fuel at which it gives off enough vapor to produce an inflammable mixture above the fuel surface when heated under standard test conditions. To obtain the flash point value of the fuel according to the ASTM D93 method, a HFP 380 Pensky Martens flash point analyser as shown in Figure 3.5 was used. Some technical data of the equipment is given in Table 3.4. The flash point is determined by heating the fuel in a small enclosed chamber until the vapors ignite when a small flame is passed over the surface of the fuel.

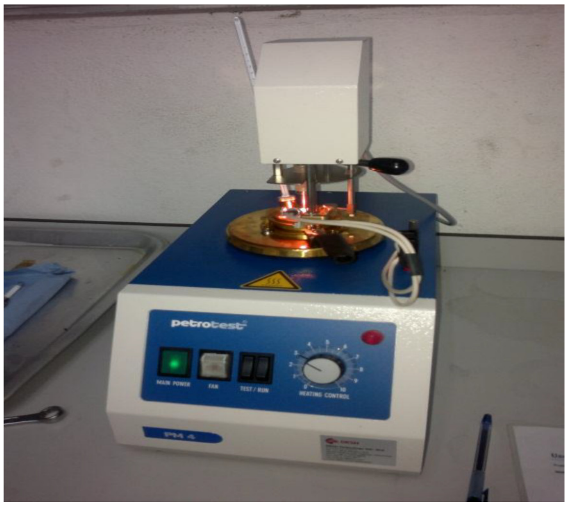


Figure 3.5: Flash Point Tester

The equipment determines the temperature where the vapor formed by the fuel would create a vapor which would then be ignited by a flame source. The test is conducted by first step is fill the fuel sample within level 70 ml in the cup with handle. The main switch is turn ON and the host then connected to the flash point device. Then the cup with fuel sample put inside the mold, also the thermometer positioned properly. Turn on the gas and light up flames at the test cover with ignition. Heating switch is then turns ON and control heating regulator up to boiling point of the sample. Sample was stirred using the hand stirrer and it was checked frequently to ensure when the flash point occurs (the flame exiting the device would burn). Temperature reading then recorded at this stage for flash point of the fuel sample.

Table 3.4: Technical Data for Flash Point Tester

Parameter	**Values**
Temperature range	Approx. +40 to +360 °C
Ignition type	Gas and electric (included)
Stirring speeds	120 or 250 rpm (selectable)
Sensing system	Differential-thermocouple
Gas connection	For propane/butane or natural gas (max. 0.05 bar)
Dimension (L×W×H)	230×470×460 mm

3.6.3 Calorific Value Measurement

The heating value of all the fuel samples used in this research work was determined using IKA C 2000 calorimeter. IKA C 2000 calorimeter system shown in Figure 3.6 can be used to determine the gross calorific value of solid and liquid materials in accordance to DIN 51900, BS 1016 T5, ISO 1928, ASTM 5468 and ASTM 4809. Some technical data of the calorimeter can be found from Table 3.5.

Figure 3.6: IKA C 2000 Calorimeter

The combustion calorimeter measures the heat that rises from burning of fuel sample. The sample is weighed into a digestion vessel and filled with oxygen. The burning process is started by means of an ignition spark. The experiment ends when the sample is fully burned. By measuring the temperature increase, the heating value of the sample can be calculated. In more detail, it can be said that combustion process in IKA C 2000 calorimeter takes place under defined conditions. To fulfill this condition, the decomposition vessel is coated with a weighed out quantity of fuel sample, the fuel sample is ignited, and the increase in temperature of the calorimeter system is measured. The specific gross calorific value of the sample is calculated from the following parameters:

- The weight of the fuel sample
- The heat capacity value of the calorimeter system.
- The increase in temperature of the water within the inner vessel of the measuring cell.

Table 3.5: Technical Data of IKA C 2000 Calorimeter

Parameters	**Value**
Duty cycle	Continuous operation
Ambient Temperature	20°C … 25°C (constant)
Ambient relative humidity	80%
Usage above sea level	2000 meters above sea level
Measurement range	40,000 J
Measuring mode	Isoperibolic 25°C Dynamic 30° C Isoperibolic 30°C Dynamic 25°C
Isoperibolic measuring time	About 22 min
Dynamic measuring time	About 10 min
Oxygen operating pressure	30 bar
Oxygen test pressure	40 bar
Cooling medium	Water via line
Dimensions	440 x 450 x 500 (W x D x H)
Weight	30 kg
Flow quantity	Min. 60 liters/hour Max. 70 liters/hour

However during an experiment, the following processes occur in the measuring cell

- The measuring cell cover starts closing automatically, once the decomposition vessel is immersed with the fuel sample in the inner vessel.
- Pure oxygen (99.95%) flows into the decomposition vessel through the oxygen filling apparatus until the required pressure has been reached (30 bars).
- Water from an external pressure source flows into the device and is heated up to the working temperature (optionally 25° C-30 °C).
- The inner vessel is filled with temperature-controlled water (at working temperature).
- The temperature of the water in the insulating outer vessel is controlled.
- With the help of ignition device, fuel sample is ignited.

3.6.4 Oxidation Stability

Biodiesel which is produced from vegetable oils is considered more vulnerable to oxidation at high temperature and contact of air, because of bearing the double bond molecules in the free fatty acid. The biodiesel and its blends stability was measured by induction period. Oxidation stability of samples was evaluated with commercial appliance Rancimat 743 as shown in Figure 3.7 applying accelerated oxidation test (Rancimat test) specified in EN 14112. The end of the induction period (IP) was determined by the formation of volatile acids measured by a sudden increase of conductivity during a forced oxidation of ester sample at 110 °C with airflow of 10 L/h passing through the sample. Some technical data is given in Table 3.6.

Figure 3.7: Rancimat 743

However during the experiment following procedure was followed:

- The heating block is heated up to the 110° C temperature.
- The measuring vessel is filled with 60 mL deionized water and placed on the Rancimat together with the measuring vessel cover. For long analysis times (> 72 h), it is recommended to increase the volume to compensate evaporation loss. An evaporation rate of 5 … 10 mL water per day has to be taken into account. It has to be ensured that the electrode is immersed into the measuring solution at any time.
- For each determination, a new reaction vessel is used. To remove particles (e.g., from the cardboard box) the reaction vessel is air-cleaned inside and outside by a sharp stream of nitrogen. Then sample is weighed directly into the reaction vessel. For liquid samples and for samples that melt at elevated temperatures a sample size of 3.0 ± 0.1 g is used. For samples with significant water content (> 5%) the sample size has to be increased to compensate the decrease in volume when the water evaporates. Ensure that the air inlet tube always immerses in the sample. Solid samples which do not melt should only cover the bottom of the reaction vessel. In this case, 0.5 … 1 g of the powdered sample is weighed into the reaction vessel.

- The reaction vessel is closed with a reaction vessel cover assembled with an air inlet tube.
- Before the determination can be started, the temperature of the heating block has to be stable. The two tubing's between Rancimat and reaction vessel and between reaction vessel and measuring vessel are connected. Then the reaction vessel is placed in the heating block and the measurement is started immediately.

Table 3.6: Technical Data of 737 Rancimat Instrument

Parameter	**Values**
Sample size	Liquid samples: 3.0 ± 0.1 g
Measuring solution	60 mL
Temperature (°C)	80-160
Gas Flow	10 L/hr
Evaluation	Induction time
Evaluation sensitivity	1.0

3.6.5 Cloud Point and Pour Point

The pour point describes a procedure for testing the fluidity of a fuel at a specified temperature. The cloud point is defined as the temperature of a liquid specimen when the smallest observable cluster of wax crystals first appears upon cooling under prescribed conditions. An automatic NTE 450 (Norma lab, France) Cloud and Pour point tester as shown in Figure 3.8 was used to measure the cloud point and pour point of the samples according to the ASTM D2500 and ASTM D93 respectively. Table 3.7 shows some technical data of cloud and pour point tester.

Table 3.7: Technical Data of NTE 450 Cloud and Pour Point Tester

Pour Point	**Cloud point**
Detection by optical fiber	Detection by ultrasonic sensor
Temperature range from -75°C to 51°C	Intervals of 1°C
Resolution: 1°C	Resolution: 0.1°C
Tilting intervals: every 3°C or 1°C	Temperature range from -75°C to 49°C

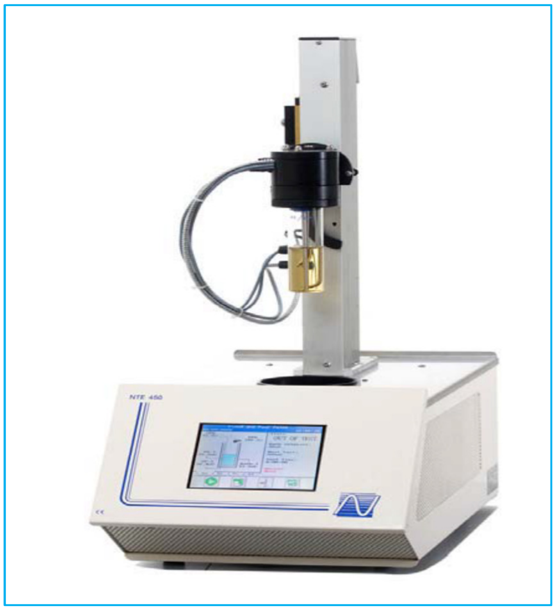


Figure 3.8: NTE 450 CP and PP Tester (Norma Lab, France)

3.6.6 Cold Filter Plugging Point

This test method covers the determination of the cold filter plugging point (CFPP) of fuels using automated equipment. The results express an estimation of the lowest temperature at which a fuel will freely flow within a fuel system. An automatic NTE 450 (Norma lab, France) cold filter plugging point tester as shown in Figure 3.9 was used to measure the cold filter plugging point (CFPP) of the samples according to the ASTM D6371 standards. Table 3.8 shows some technical data of cold filter plugging point tester.

Figure 3.9: NTE 450 CFPP Tester

Table 3.8: Technical Data of NTE 450 Cold Filter Plugging Point Tester

Parameter	Values
Detection by	Optical cell
Temperature range	-80°C to 20°C
Temperature measurement resolution	1°C
Tilting intervals	every 3°C

3.6.7 Determination of Acid Value, the Saponification Number (SN), Iodine Value (IV) and Cetane Number (CN)

Acid value is the number of milligrams of potassium or sodium hydroxide necessary to neutralize the free acid in 1 g of sample. The acid value can be calculated using the following equation:

$$AV = \frac{MW \times N \times V}{W} \quad (3.1)$$

Where,

MW ≡ Molecular weight of potassium hydroxide (KOH)

N≡ Normality of sodium hydroxide (KOH) solution.

V≡ Volume of sodium hydroxide (KOH) solution used in titration.

W ≡ Weight of oil sample

The saponification numbers (SN), iodine value (IV) and cetane number (CN) of the methyl esters of were calculated empirically from its fatty acid methyl ester compositions with the help of Eqs. (3.2), (3.3) and (3.4), respectively (Devan 2009b):

$$CN= 46.3+ (5458/SV) - (0.225 \cdot IV) \quad (3.2)$$

$$SN= SUM (560 \cdot A_i)/M_{Wi} \quad (3.3)$$

$$IV= SUM (254 \cdot A_i \cdot D)/M_{Wi} \quad (3.4)$$

Where A_i is the percentage of each component, D is the number of double bonds and MW_i molecular mass of each component.

3.7 Biodiesel-Diesel Blending

Each test fuel blend was prepared prior to the properties test and engine test. In this respect, the test fuels were blended for 20 minutes by using a homogenizer device at a speed of 2000 rpm. The homogenizer was fixed on a clamp on a vertical stand as shown in Figure 3.10, which allows changing of the homogenizer’s height. To mix the fuels by using the homogenizer, the plug is turned ON and the appropriate speed is selected by using the selector which is located on top of the homogenizer.

Figure 3.10: Biodiesel Blending Process

In this study the effect of biodiesel-diesel blending by a percentage of (10-90% v/v) on some physical and chemical properties has been studied and presented. These include flash point, viscosity, cloud point, pour point and cold filter plugging point. In this paper, polynomial curve fitting method was used to estimate the properties of other biodiesel blends. This method is an attempt to describe the relationship between variable X as a function of available data and a response Y, which seeks to find a smooth curve that best fits the data. Mathematically, a polynomial of order k in X is expressed in the following form:

$$Y = C_0 + C_1X + C_2X^2 + \ldots\ldots\ldots + C_kX^k \qquad (3.5)$$

3.8 Engine Set-Up and Engine Performance Procedure

The experimental investigation was carried out using 13 fuel samples including diesel fuel and (B5, B10, B15, B20) of each feedstocks. These blends was chosen based on the reports by the researchers that up to 20% of biodiesel blend can be used in a diesel engine without any modification. The blend compositions of all fuel samples are given in Table 3.9. The engine used is a Mitsubishi Pajero (model 4D56T) multi-cylinder diesel engine coupled with an eddy current dynamometer. Figure 3.11 shows the test rig of the engine and Figure 3.12 shows the schematic of experimental set-up. The detailed specification of the engine is shown in Table 3.10. In order to carry out engine performance test, the engine was run at various speeds range from 1000 rpm to 4000 rpm at an interval of 500 rpm at full load conditions. The engine was connected with test bed and a computer data acquisition system which collects signal, rectify, filter and convert the signal to the data to be read.

Table 3.9: Blend Fuel Compositions (% Vol)

No.	Fuel Samples	Samples description
01	B0	Diesel fuel
02	PB5	5% Palm biodiesel + 95% diesel fuel
03	PB10	10% Palm biodiesel + 90% diesel fuel
04	PB15	15% Palm biodiesel + 85% diesel fuel
05	PB20	20% Palm biodiesel + 80% diesel fuel
06	JB5	5% Jatropha biodiesel + 95% diesel fuel
07	JB10	10% Jatropha biodiesel + 90% diesel fuel
08	JB15	15% Jatropha biodiesel + 85% diesel fuel
09	JB20	20% Jatropha biodiesel + 80% diesel fuel
10	MB5	5% Moringa biodiesel + 95% diesel fuel
11	MB10	10% Moringa biodiesel + 90% diesel fuel
12	MB15	15% Moringa biodiesel + 85% diesel fuel
13	MB20	20% Moringa biodiesel + 80% diesel fuel

In order to carry out the engine performance tests for this study such as engine torque, brake power, brake specific fuel consumptions, brake specific air consumptions, engine test conditions were monitored by REO-DCA controller connected through a desktop to the engine test bed. All the performance data was measured at step RPM test mode. At every 500 rpm increments, engine stabilizes for 20 seconds and acquires data for next 20 seconds.

For performance test, each fuel sample has been tested for three times and their results are averaged. The data logged by the computer are:

- Engine speed
- Dynamometer load
- Throttle position
- Fuel flow rate
- Air flow rate
- Fuel temperature
- Air temperature
- Lube oil temperature
- Coolant temperature
- Inlet and exhaust manifold temperature
- Engine torque
- Brake power
- Brake specific fuel consumption

Before the engine and dynamometer are started, several precautions had to be taken into consideration.

(a) The motor was switched ON to supply cooling water to the dynamometer and the flow out water was controlled to maintain a suitable flow rate by using the water outlet valve.

(b) It was ensured that the water level of the main water tank was always sufficient during the engine test.

(c) The engine lube oil was checked with the dipstick indicator.

(d) The cooling water inlet was adjusted by using the valves to control the flow rate in order to maintain the inlet temperature.

Table 3.10: Specifications of the Engine

Parameter	Unit	Description
Engine type		4 cylinder inline
Displacement	(L)	2.5
Cylinder bore x stroke	(mm)	92 x 96
Compression ratio		21:1
Maximum engine speed	(rpm)	4200
Maximum power	(kW)	55
Fuel system		Distribution type jet pump (indirect injection)
Lubrication System		Pressure feed
Combustion chamber		Swirl type
Cooling system		Radiator cooling

Figure 3.11: Engine Test Bed

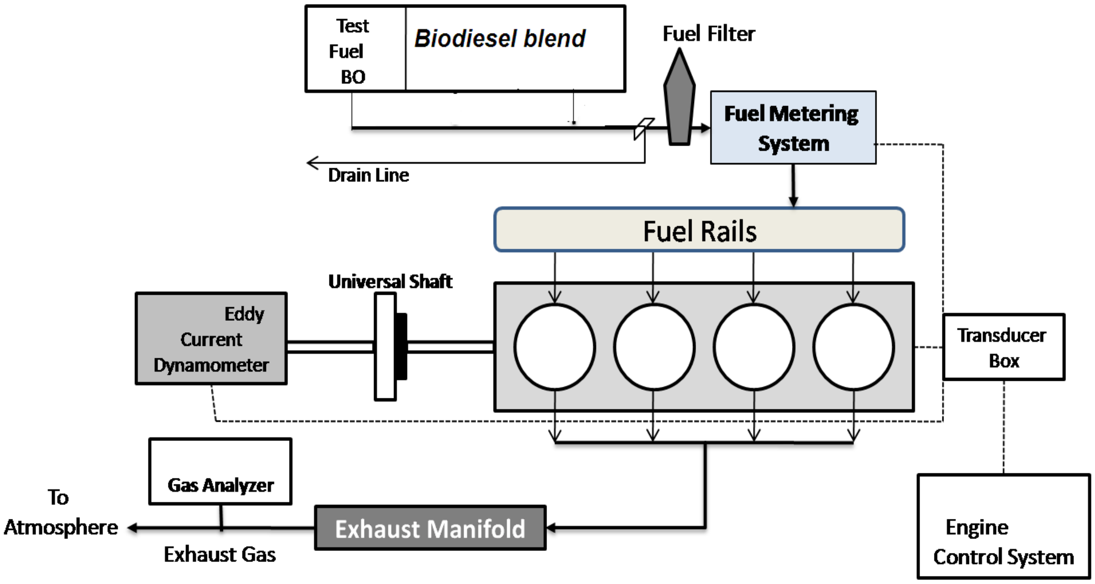


Figure 3.12: Schematic Diagram of Engine Test Bed

3.8.1 Dynamometer

The dynamometer is used to exert a fixed loading onto the engine for the purpose of analysis and it also measures the speed at which the engine is rotating. The dynamometer is connected to the engine by a shaft which is enclosed in a steel casing between the test engine and the dynamometer. The dynamometer is cooled by the cooling system which is located in front of it. The cooling system has a pump which moves the water through the dynamometer into the radiator where it will be cooled by the air pushed by the fan and enters the dynamometer to complete the cycle. Figure 3.13 shows the dynamometer of the diesel engine.

Figure 3.13: Dynamometer

The dynamometer is connected to the controller box where the measured speed and also the torque are displayed. The dynamometer is turned ON by switching both the switches at the dynamometer controller to ‘ON’. The torque is adjusted by turning the red knob on the dynamometer controller. The knob is turned in the counter clockwise direction to increase the torque and the knob is turned in the clockwise direction to reduce the torque. Caution steps should be taken as not to suddenly increase the torque of the dynamometer which could cause the shaft to break under the sudden increase in stress. Also, load should not be increased too much that will cause a lot of stress on the engine and would stop the engine.

3.9 Apparatus for Engine Emission Studies

A BOSCH exhaust gas analyzer (model BEA-350) was used as shown in Figure 3.14 to measure the exhaust emission gases emission of NO and HC in ppm while CO and CO_2 in volume percent. The details of gas analyzer are shown in Table 3.11. In this research work exhaust emission was measured at various speeds range from 1000 rpm to 4000 rpm at an interval of 500 rpm at full load conditions by inserting probe into the tail pipe. First the engine was run using diesel fuel to get baseline data and other fuel blends were tested accordingly.

To get the average values, all tests were repeated three times. The technology of this analyzer consisted of automatic measurements with microprocessor control and self-test, auto calibration before every analysis, and a high degree of accuracy in analysis of low concentrations of gases found in engine fitted with catalytic converter. After the instrument is switched ON it takes three minutes to warm up. During this time no measurement is possible. After a system adjustment has been conducted with zero gas, the measurement can be taken. Before every measurement the zero point of the analysis system is automatically adjusted with zero gas after the pump is switched on. During the first 15 seconds of the 30 seconds adjustment, zero is indicated in the indicator panels for the gases and the particular upper limit of the effective range is indicated for 15 seconds. During the test, the water condensed in the hose connecting the probe and it is collected in the condensate container and automatically sucked out. However a new condensate filter has to be installed by switching of the measured-gas pump, if the present is badly fouled.

Figure 3.14: Bosch Gas Analyzer (BEA 350)

Table 3.11: Details of the Exhaust Gas Analyzer (BEA-350)

Equipment	**Method**	**Measurement**	**Upper limit**	**Accuracy**	**Percentage uncertainties**
BOSCH gas analyser	Non-dispersive infrared	CO	10.00 vol%	±0.001 vol%	0.002 vol%
	Non-dispersive infrared	CO_2	18.00 vol%	±0.001 vol%	0.150 vol%
	Flame ionization detector (FID)	HC	9999 ppm	±l ppm	2 ppm
	Electro-chemical transmitter	NO	5000 ppm	±1 ppm	21 ppm

CHAPTER 4

RESULT AND DISCUSSIONS

4.0 Introduction

In this chapter, the physical and chemical properties of crude edible and non-edible oil feedstocks was presented followed by the properties include kinematic viscosity, density, viscosity index, cloud point, pour point, and cold filter plugging point, flash point, calorific value and oxidation stability of biodiesel synthesized from edible and non-edible feedstocks. The physical and chemical properties of biodiesel-diesel blends ratios of (B0-B100) were fully covered and presented. Moreover, the polynomial curve fitting method was used to see the effect of blending on fuel properties and to predict the properties of biodiesel blends at any blends ratio. Finally, data of engine performance and emission characteristics using a total of 12 fuel samples (B5, B10, B15 and B20 of each biodiesel) were presented and compared with that of diesel fuel.

4.1 Physico-Chemical Properties of Crude Palm, *Jatropha Curcas* and *Moringa Oleifera* Oil

The feedstock characteristics such as FFA and acid values influence the biodiesel production process selection and final properties of biodiesel. Moreover, feedstocks with high MIU and titter require extra processing steps like filtration, centrifuging and heating. Table 4.1 shows the main findings of the physical and the chemical properties of crude palm, *Jatropha curcas* and *Moringa oleifera* oil.

Table 4.1: Physico-Chemical Properties of Crude Palm, *Jatropha Curcas* and *Moringa Oleifera* Oil

Properties	**Units**	**Standards**	**Palm oil**	**Jatropha oil**	**Moringa oil**
Dynamic viscosity	mPa.s	ASTM D445	36.30	31.52	38.90
Kinematic viscosity at 40 °C	mm^2/s	ASTM D445	40.40	34.93	43.33
Kinematic viscosity at 100 °C	mm^2/s	ASTM D445	8.43	7.81	8.91
Viscosity Index	-	N/A	192.1	204.5	193.1
Density at 15 °C	kg/m^3	ASTM D4052	898.4	902.5	897.5
Flash point	°C	ASTM D93	165	220	268.5
Pour point	°C	ASTM D97	9	-3	11
Cloud point	°C	ASTM D2500	8	-2	10
Calorific value	MJ/kg	ASTM D240	39.44	38.66	38.05
Acid value	mgKOH/g oil	ASTM D664	3.47	10.7	8.62

From Table 4.1 it can be seen that *Moringa oleifera* oil has highest kinematic viscosity of 43.33 mm^2/s at 40 °C and 8.91 mm^2/s at 100 °C, dynamic viscosity 38.90 mPa.s at 40 °C while Palm oil have kinematic viscosity of 40.40 mm^2/s at 40 °C and 8.43 mm^2/s at 100 °C, dynamic viscosity 36.30 mPa.s at 40 °C and *Jatropha curcas* oil have kinematic viscosity of 34.93 mm^2/s at 40 °C and 7.81 mm^2/s at 100 °C, dynamic viscosity 31.52 mPa.s at 40 °C.

It is clear that all crude oil samples have higher viscosity. These high values of viscosities can negatively affect the volume flow and injection spray characteristics in the engine. At low temperature it may even compromise the mechanical integrity of the injection pump drive systems (Jayed et al. 2009). Therefore, it is suggested that oil from the crops should be either blended with diesel fuel or transesterified to biodiesel to reduce the viscosity and density properties when used in CI engines.

The density results showed that the *Jatropha curcas* oil possesses highest density 902 kg/m^3 followed by Palm oil and *Moringa oleifera* oil which have 898.5 and 897.5 kg/m^3 respectively.

The flash point results showed that *Moringa oleifera* oil possesses highest flash point 265.4 °C followed by *Jatropha curcas* and palm oil which have 220 °C and 165°C respectively. All of these crude oils have very high flash points (>160 °C) which indicate that these oils are very safe for transportation, handling and storage.

Calorific value is an important parameter in the selection of a fuel. If the fuel has higher calorific value then it will have tendency to produce more power in the engine. The result from Table 4.1 shows that Palm oil possesses highest calorific value 39.44 MJ/kg followed by Jatropha oil (38.66 MJ/kg) and *Moringa oleifera* oil (38.05 MJ/kg) respectively.

The acid value results showed that the crude *Jatropha curcas* oil possesses highest acid value of 10.7 mg KOH/g oil followed by Moringa oil (8.62 KOH/g oil) and Palm oil (3.47 mg KOH/g oil) respectively. So it is easier to convert palm oil into palm biodiesel compared to Jatropha and Moringa oil respectively.

4.2 Characterization of Palm, *Jatropha Curcas* and *Moringa Oleifera* Biodiesel

4.2.1 Properties Analysis

The quality of biodiesel depends upon the feedstocks quality, chemical composition of feedstock, production process, storage and handling process. Biodiesel quality is assessed through the determination of physical and chemical properties. The physical and chemical properties of Palm, *Jatropha curcas* and *Moringa oleifera* are presented in Table 4.2.

Table 4.2: Physico-Chemical Properties of Palm, *Jatropha Curcas* and Moringa Biodiesel compared with diesel fuel

Properties	**Units**	**Standards**	**Palm Biodiesel**	**Jatropha Biodiesel**	**Moringa Biodiesel**	**Diesel**
Dynamic viscosity	mPa.s	ASTM D445	3.97	4.09	4.34	2.69
Kinematic viscosity at 40°C	mm^2/s	ASTM D445	4.62	4.73	5.05	3.23
Kinematic viscosity at 100°C	mm^2/s	ASTM D445	1.77	1.81	1.84	1.24
Density	kg/m^3	ASTM D1298	858.9	865.7	869.6	827.2
Viscosity index	-	N/A	195.8	214.7	184.6	90
Flash point	°C	ASTM D93	182.5	184.5	180.5	68.5
Cloud point	°C	ASTM D2500	10	3	19	8
Pour point	°C	ASTM D97	11	3	19	0
Cold filter plugging point	°C	ASTM D6371	11	10	18	5
Sulphur content	ppm	ASTM D5433	5.23	5.95	5.95	-
Calorific value	MJ/kg	ASTM D240	39.90	39.82	40.05	45.30
Iodine value	g I/100g	N/A	61	99	77.5	-
Saponification value	-	N/A	206	202	199	-
Acid value	mg KOH/g	ASTM D664	0.05	0.05	0.05	-
Oxidation stability	h	EN ISO 14112	2.41	3.02	26	>110
Cetane number	-	ASTM D613	59	51	56	48
Carbon Conradson	%	ASTM D4530	0	0	0	-

The main findings from properties test is that Palm biodiesel (PB) possesses the lowest kinematic viscosity at 40°C of 4.62 mm^2/s followed by *Jatropha curcas* biodiesel (JB) of 4.73 mm^2/s and *Moringa oleifera* biodiesel (MB) of 5.05 mm^2/s. Therefor palm biodiesel is suitable for combustion in a diesel engine compared to Jatropha and Moringa biodiesel.

The results of density showed that the PB has lowest density of 858.9 kg/m^3 followed by JB of 865.7 kg/m^3 and MB of 869.6 kg/m^3. The results of cold flow plugging point properties showed that PB has higher CFPP of 10°C followed by the JB of 11°C and MB of 18°C. On the other hand, it was found that JB has the CP & PP of 3°C & 3°C, (PB) has the CP & PP of 10°C & 11°C, and MB has the CP & PP of 19°C & 19°C respectively. The results of the oxidation stability showed that MB has the good oxidation stability of 26 h followed by JB of 3.2 h and PB of only 2.41 h. Moreover, MB possesses the highest calorific value of 40.05 MJ/kg compared to PB of 39.90 MJ/kg and JB of 39.82 MJ/kg respectively. The results of flash point show that JB has the highest flash point of 184.5°C, followed by PB of 182.5°C and MB of 180.5°C. So it is seen that Jatropha biodiesel have good cold flow properties and is safer to store compared to Palm and Moringa biodiesel.

4.2.2 Fatty Acids Composition of Palm, *Jatropha Curcas* and *Moringa Oleifera* Biodiesel

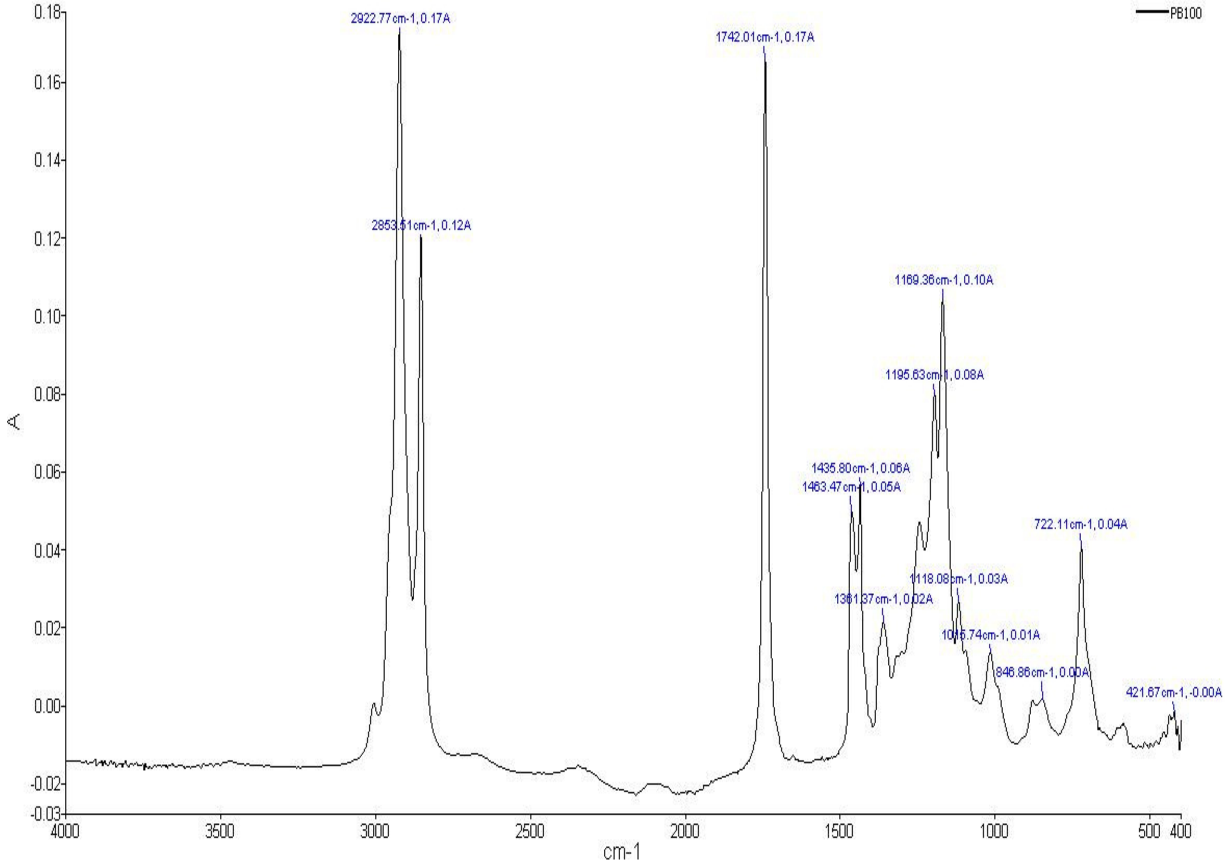
Fatty acid without double bond is known as saturated fatty acids and Fatty acid containing double bond is termed as unsaturated fatty acids. The results of FAC of Palm biodiesel (PB), *Jatropha curcas* biodiesel (JB) and *Moringa oleifera* biodiesel (MB) are shown in Table 4.3. It was found that PB contained (44.4%) saturated and (55.6%) unsaturated fatty acids, JB contained (22.6%) saturated and (77.4%) unsaturated fatty acids and MB contained (18.6%) saturated and (81.4%) unsaturated fatty acids respectively.

Table 4.3: Fatty Acid Composition of Palm, Jatropha and Moringa Biodiesel

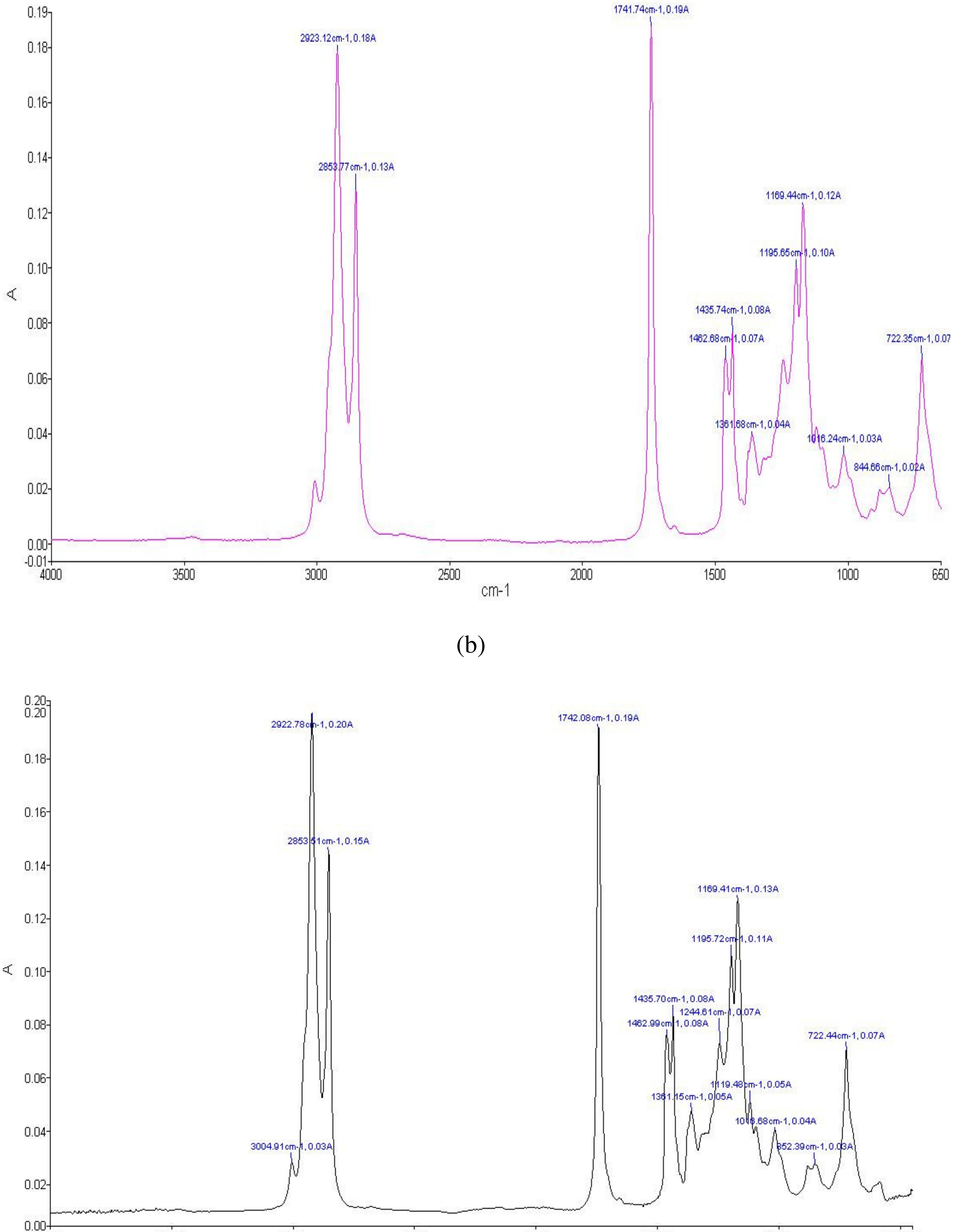
Sl. No.	Fatty acid	Molecular weight	Structure	Systematic name	Formula	PB (%)	JB (%)	MB (%)
01	Lauric	200	12:0	Dodecanoic	$C_{12}H_{24}O_2$	-	0.1	0
02	Myristic acid	228	14:0	Tetradecanoic	$C_{14}H_{28}O_2$	-	0.1	0.1
03	Palmitic	256	16:0	Hexadecanoic	$C_{16}H_{32}O_2$	40.5	14.6	7.9
04	Palmitoleic	254	16.1	hexadec-9-enoic	$C_{16}H_{30}O_2$	-	0.6	1.7
05	Stearic	284	18:0	Octadecanoic	$C_{18}H_{36}O_2$	4.1	7.6	5.5
06	Oleic	282	18:1	cis-9-Octadecenoic	$C_{18}H_{34}O_2$	43.4	44.6	74.1
07	Linoleic	280	18:2	cis-9-cis-12 Octadecadienoic	$C_{18}H_{32}O_2$	12.0	31.9	4.1
08	Linolenic	278	18:3	cis-9-cis-12	$C_{18}H_{30}O_2$	-	0.3	0.2
09	Arachidic	312	20:0	Eicosanoic	$C_{20}H_{40}O_2$	-	0.2	2.3
10	Eicosanoic	310	20:1	cis-11-eicosenoic	$C_{20}H_{38}O_2$	-	-	1.3
11	Behenic	340	22:0	Docosanoic	$C_{22}H_{44}O_2$	-	-	2.8
12	Other					0	0	0
Saturated						44.6	22.6	18.6
Monounsaturated						43.4	45.2	77.1
Polyunsaturated						12.0	32.2	4.3
Total						100	100	100

4.2.3 Structural Analysis

The structural analysis of Palm, *Jatropha curcas* and *Moringa oleifera* biodiesel was done by FT-IR analysis. Figure 4.1 shows the Fourier transform infrared (FT-IR) spectrum of the Palm, *Jatropha curcas* and *Moringa oleifera* biodiesel. The characteristics peaks of the Palm, *Jatropha curcas* and *Moringa oleifera* biodiesel are shown in Table 4.4.



(a)



(b)

(c)

Figure 4.1: FT IR Analysis of (a) Palm, (b) *Jatropha Curcas* and (c) *Moringa Oleifera* Biodiesel

4.3 Effect of Biodiesel-Diesel Blending on Fuel Properties

It was found that blending of biodiesel with diesel has resulted in much improvement in kinematic viscosity, density, calorific value, oxidation stability. However, flash point and viscosity index decrease as the percentage of diesel increases in the blend. The next section will discuss how to establish a mathematical correlation between the blends ratio and physical and chemical properties.

Table 4.4: Characteristics Peak of PB, JB and MB in FT IR Spectra

Absorption bands (cm^{-1}) PB	**Absorption bands (cm^{-1}) JB**	**Absorption bands (cm^{-1}) MB**	**Functional group**	**Absorption intensity**
2922.77	2912	2922.78-3004.91	C-H stretching vibration	Strong
2853.51	2853	2853.5	CH_2 asymmetric and symmetric vibration	Strong
1742	1741	1742.08	C=O stretching vibration	Strong
1435.80-1463.47	1435-1462	1435.7-1462.99	CH_2 shear type vibration	Middling
1361.37	1361	1361.15	CH_3 bending vibration	Middling
1118.08-1195.63	1169-1195	1119.48-1195.72	C-O-C symmetric stretching vibration	Middling
1016.74	1016	1016.68	C-O-C anti-symmetric stretching vibration	Weak
848.86	844	852.39	Epoxy ring vibration	Middling
722.11	722	722.44	CH_2 plane rocking vibration	Weak

4.3.1 Mathematical Relationship between Blends Ratio and Physico-Chemical Properties

Based on the data of all biodiesel-diesel blend in Appendix B, mathematical equations were developed for the calculation of oxidation stability (OS), viscosity (KV), density (D), viscosity index (VI), calorific value (CV) and flash point (FP) of PB, JB and MB blends with diesel. The next section will explain the results of this study in detail.

4.3.1.1 Kinematic Viscosity (KV)

Figures 4.2 (a-c) and Figures 4.3 (a-c) show the correlations between kinematic viscosity at 40°C and 100°C of PB, JB and MB and their blends with diesel. As can be seen, the kinematic viscosities of PB, JB and MB decrease remarkably with the increasing percentage of diesel in the blends. The viscosity values of PB, JB and MB and their blends with diesel were correlated using Linear Regression Analysis (LRA). The equations between kinematic viscosity and blends ratio are:

For (PB-diesel blends):

KV at 40°C = $1.3841x + 3.2024$ $x \equiv$ (%PB-diesel blends) (4.1)

$R^2 = 0.9948$

KV at 100°C = $0.4976x + 1.2616$ $x \equiv$ (%PB-diesel blends) (4.2)

$R^2 = 0.9941$

For (JB-diesel blends):

KV at 40°C = $1.4491x + 3.2782$ $x \equiv$ (%JB-diesel blends) (4.3)

$R^2 = 0.997$

KV at 100°C = $0.5409x + 1.2786$ $x \equiv$ (%JB-diesel blends) (4.4)

$R^2 = 0.99$

For (MB-diesel blends)

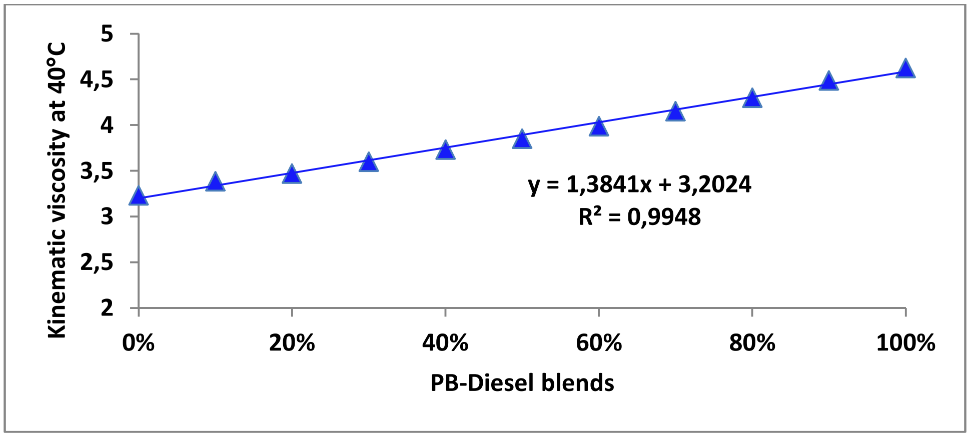
KV at 40°C = $1.7446x + 3.2962$ $x \equiv$ (%MB-diesel blends) (4.5)

$R^2 = 0.996$

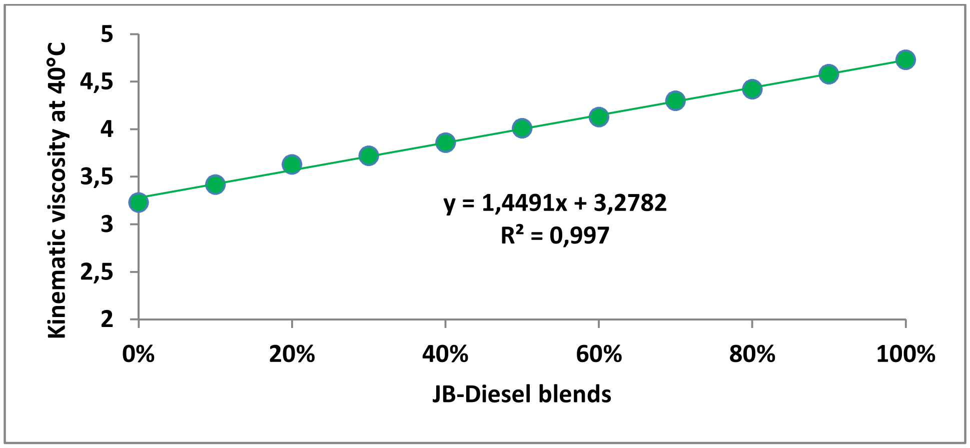
KV at 100°C = $0.581x + 1.2795$ $x \equiv$ (%MB-diesel blends) (4.6)

$R^2 = 0.9895$

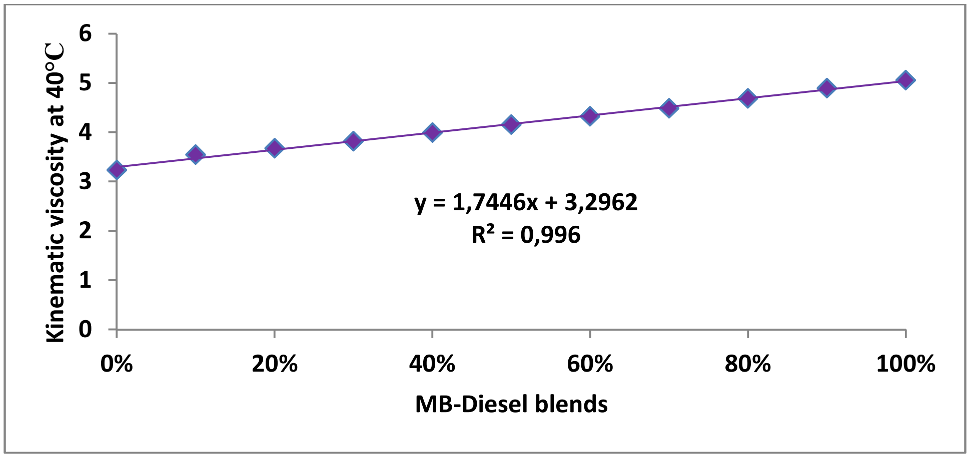
It can be observed that the coefficient of regression values indicate that there is a high regression between kinematic viscosity and biodiesel-diesel blends.



(a)

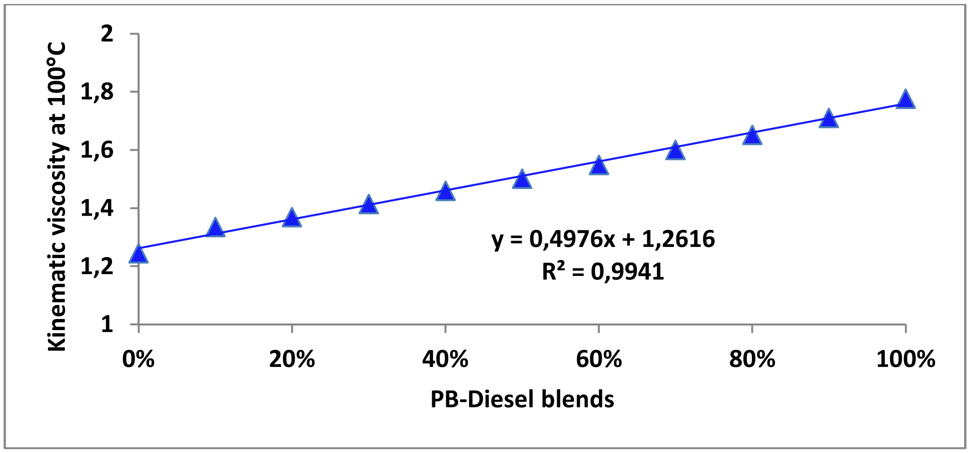


(b)

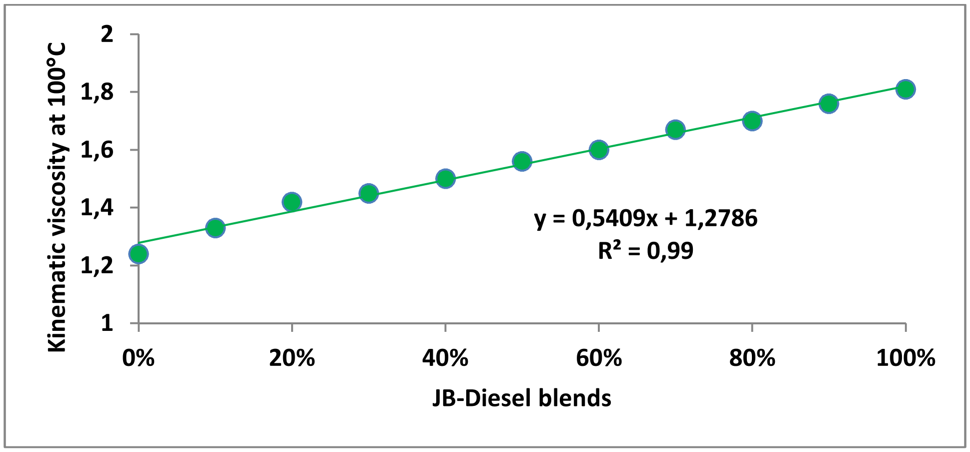


(c)

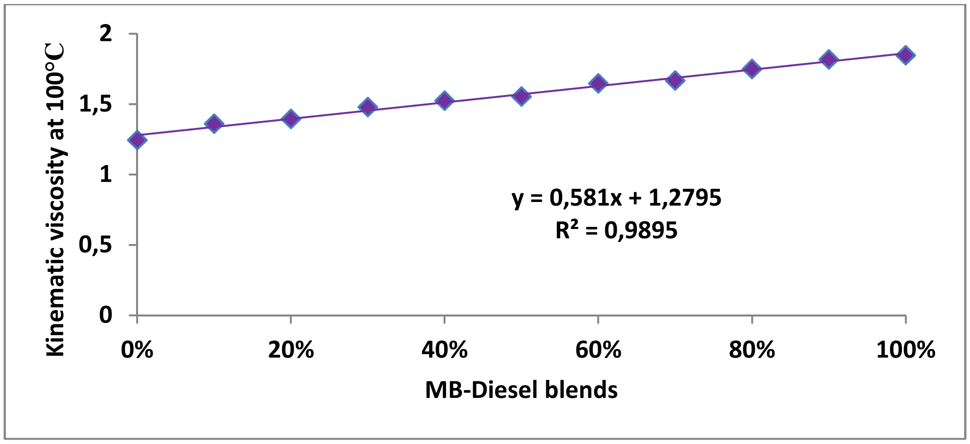
Figure 4.2: Effect of (a) PB-Diesel Blending (b) JB-Diesel Blending (c) MB-Diesel Blending on Kinematic Viscosity at 40°C



(a)



(b)



(c)

Figure 4.3: Effect of (a) PB-Diesel Blending (b) JB-Diesel Blending (c) MB-Diesel Blending on Kinematic Viscosity at 100°C

4.3.1.2 Density (D)

Figure 4.4 (a-c) shows the correlations between density of PB, JB and MB and their blends with diesel. As can be seen, the densities of PB, JB and MB decrease remarkably with the increasing percentage of diesel in the blends. The density values of PB, JB and MB and their blends with diesel were correlated using Linear Regression Analysis (LRA). The equations between density and blends ratio are:

For (PB-diesel blends):

$D = 0.0238x + 0.8353$ $x \equiv$ (%PB-diesel blends) (4.7)

$R^2 = 0.9979$

For (JB-diesel blends):

$D = 0.0382x + 0.8269$ $x \equiv$ (%JB-diesel blends) (4.8)

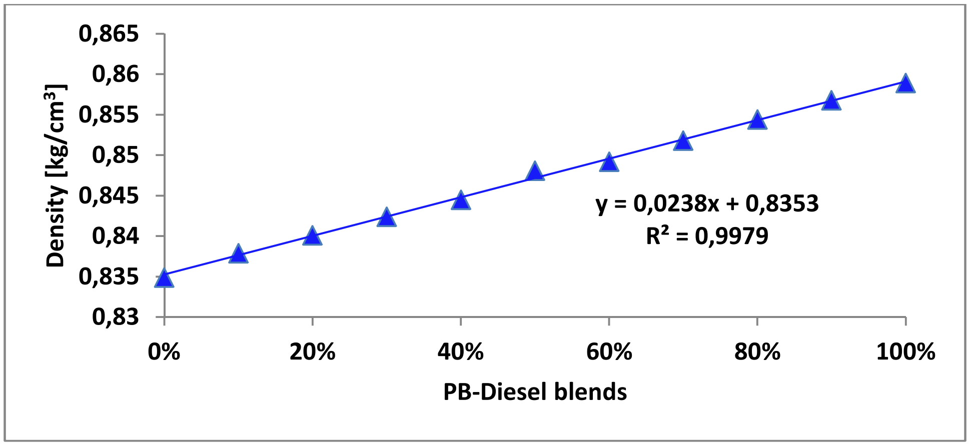
$R^2 = 0.9985$

For (MB-diesel blends):

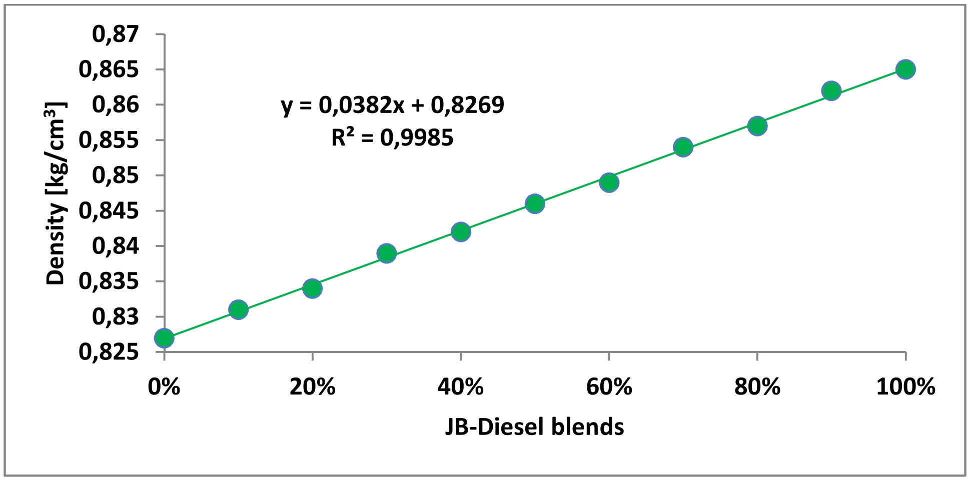
$D = 0.0328x + 0.827$ $x \equiv$ (%MB-diesel blends) (4.9)

$R^2 = 0.9993$

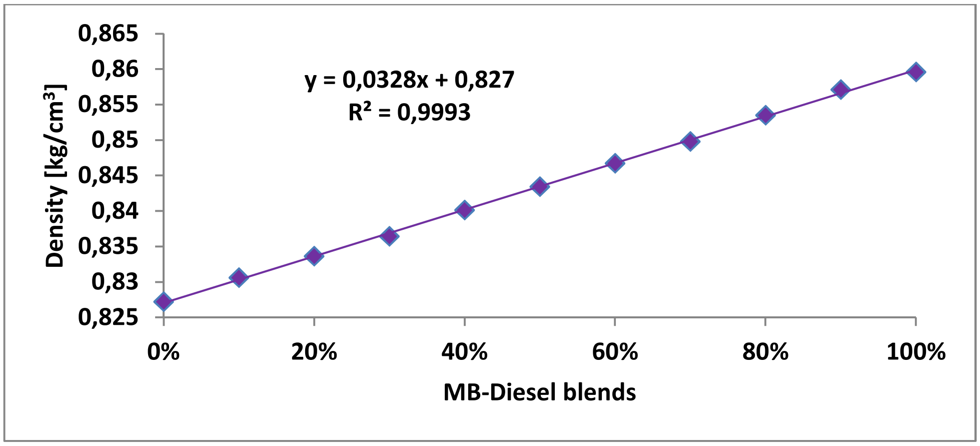
It can be observed that the coefficient of regression values show a high regression between density and biodiesel-diesel blends.



(a)



(b)



(c)

Figure 4.4: Effect of (a) PB-Diesel Blending (b) JB-Diesel Blending (c) MB-Diesel Blending on Density

4.3.1.3 Viscosity Index (VI)

Figure 4.5 (a-c) shows the correlations between viscosity index of PB, JB and MB and their blends with diesel. As can be seen, the viscosity index values of PB, JB and MB decrease remarkably with the increasing percentage of diesel in the blends. The viscosity index values of PB, JB and MB and their blends with diesel were correlated using Polynomial Regression Analysis (PRA). The equations between viscosity index and blends ratio are:

For (PB-diesel blends):

$VI = 254.33x^3 - 495.72x^2 + 341.41x + 97.911$ $\quad x \equiv$ (%PB-diesel blends) (4.10)

$R^2 = 0.9658$

For (JB-diesel blends):

$VI = 310.12x^3 - 573.53x^2 + 384.01x + 98.238$ $\quad x \equiv$ (%JB-diesel blends) (4.11)

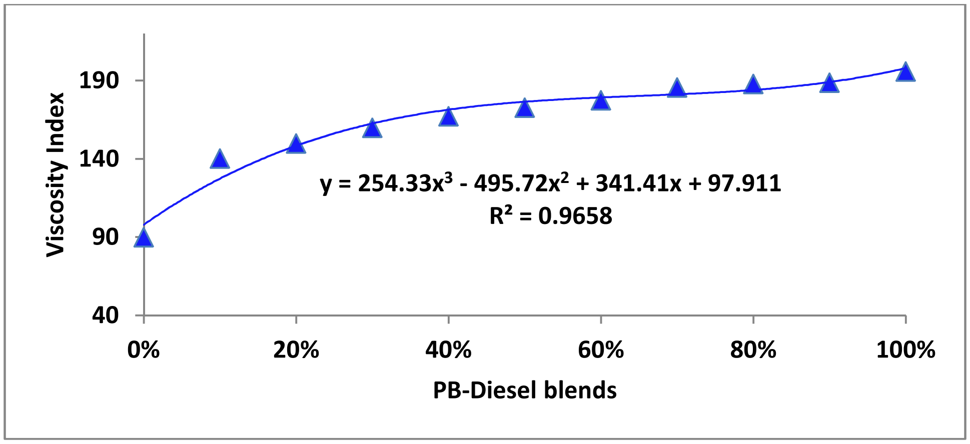
$R^2 = 0.973$

For (MB-diesel blends):

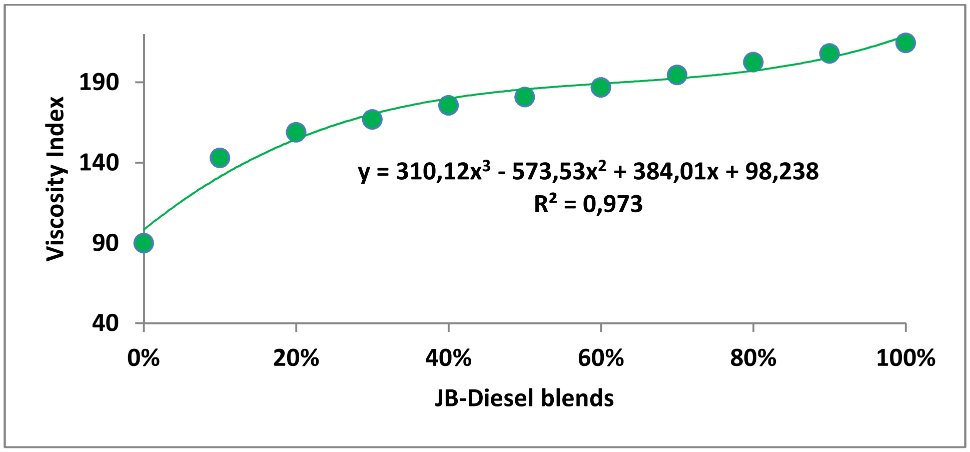
$VI = 97.909x + 91.236$ $\quad x \equiv$ (%MB-diesel blends) (4.12)

$R^2 = 0.9732$

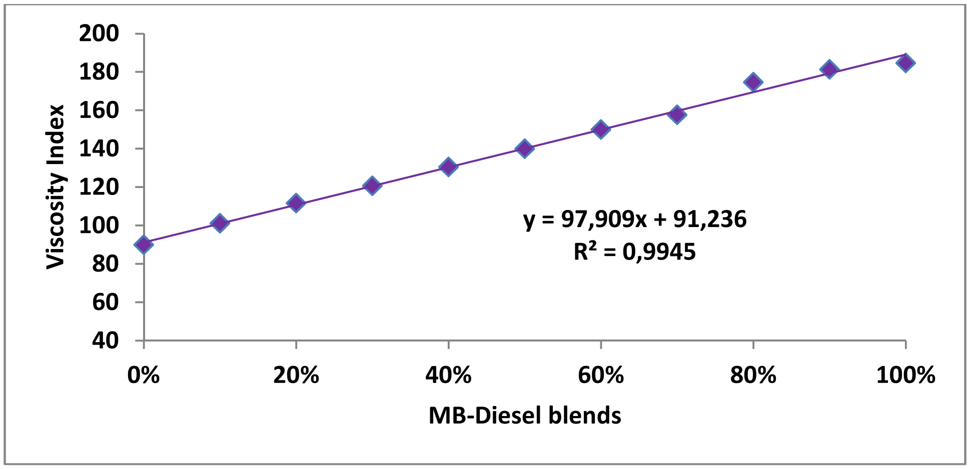
It can be observed that the coefficient of regression values show a high regression between viscosity index and biodiesel-diesel blends.



(a)



(b)



(c)

Figure 4.5: Effect of (a) PB-Diesel Blending (b) JB-Diesel Blending (c) MB-Diesel Blending on Viscosity Index

4.3.1.4 Calorific Value (CV)

Figure 4.6 (a-c) shows the correlations between calorific value of PB, JB and MB and their blends with diesel. As can be seen, the calorific values of PB, JB and MB increase remarkably as the volume of biodiesel in the blend gets smaller. The calorific values of PB, JB and MB and their blends with diesel were correlated using Linear Regression Analysis (LRA). The equations between calorific value and blends ratio are:

For (PB-diesel blends):

$CV = -5.4651x + 45.1$ $x \equiv$ (%PB-diesel blends) (4.13)

$R^2 = 0.9917$

For (JB-diesel blends):

$CV = -5.6472x + 45.215$ $x \equiv$ (%JB-diesel blends) (4.14)

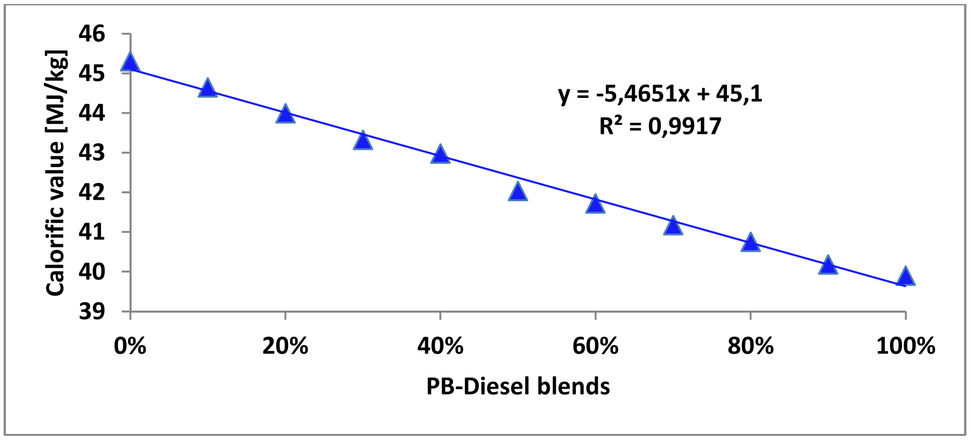
$R^2 = 0.9932$

For (MB-diesel blends):

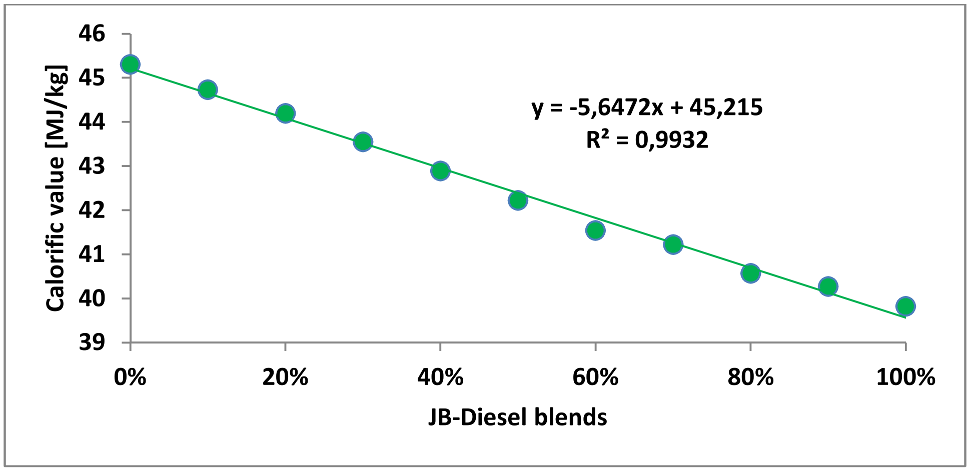
$CV = -5.361x + 45.279$ $x \equiv$ (%MB-diesel blends) (4.15)

$R^2 = 0.9946$

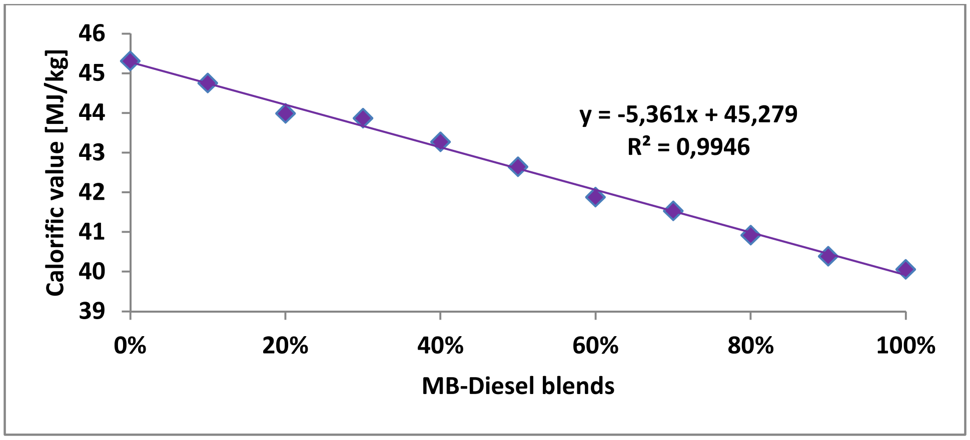
It can be observed that the coefficient of regression values show a high regression between calorific value and biodiesel-diesel blends.



(a)



(b)



(c)

Figure 4.6: Effect of (a) PB-Diesel Blending (b) JB-Diesel Blending (c) MB-Diesel Blending on Calorific Value

4.3.1.5 Oxidation Stability (OS)

Figure 4.7 (a-c) shows the correlation between oxidation stability of PB, JB and MB and their blends with diesel. As can be seen, the oxidation stability values of PB, JB and MB increase with the increasing percentage of diesel in the blends. The oxidation stability values of PB, JB and MB and their blends with diesel were correlated using Polynomial Regression Analysis (PRA). The equations between oxidation stability and blends ratio are:

For (PB-diesel blends):

$OS = -417.44x^3 + 893.48x^2 - 641.88x + 165.28$ $x \equiv$ (%PB-diesel blends) (4.16)

$R^2 = 0.9828$

For (JB-diesel blends):

$OS = -219.76x^3 + 471.04x^2 - 334.63x + 84.747$ $x \equiv$ (%JB-diesel blends) (4.17)

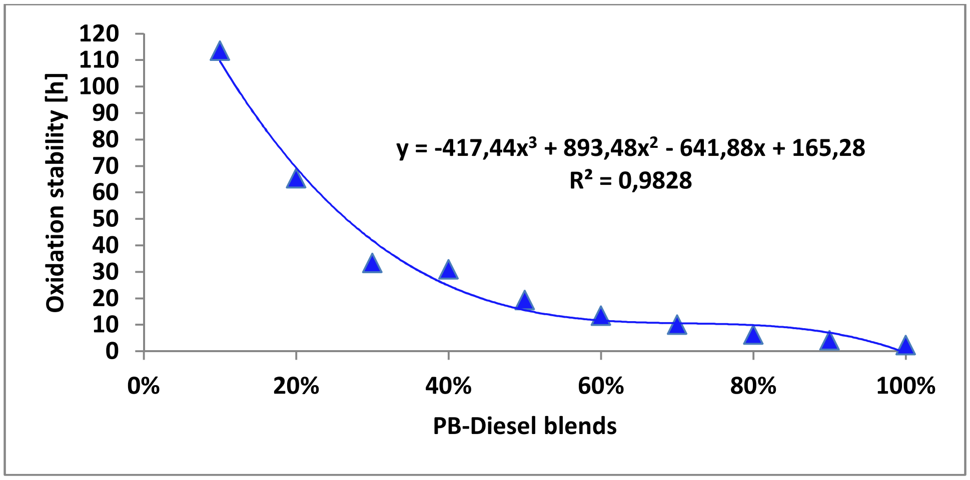
$R^2 = 0.9855$

For (MB-diesel blends):

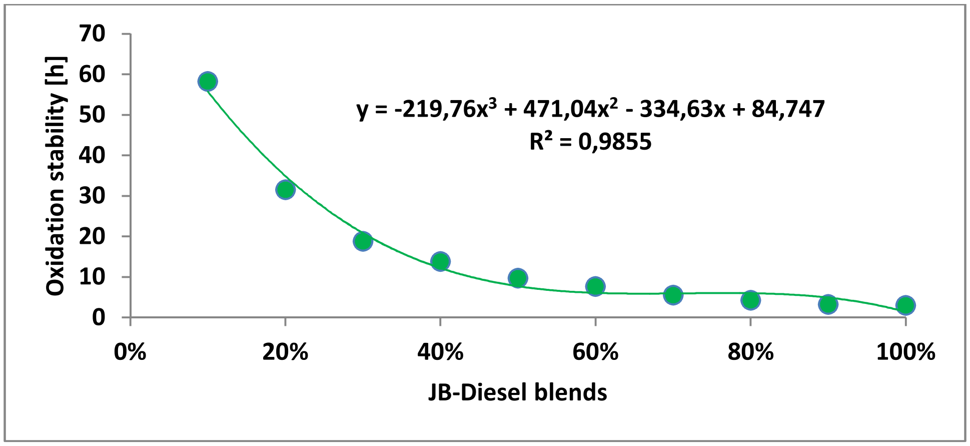
$OS = -533.76x^3 + 1010.4x^2 - 684.27x + 235.91$ $x \equiv$ (%MB-diesel blends) (4.18)

$R^2 = 0.9943$

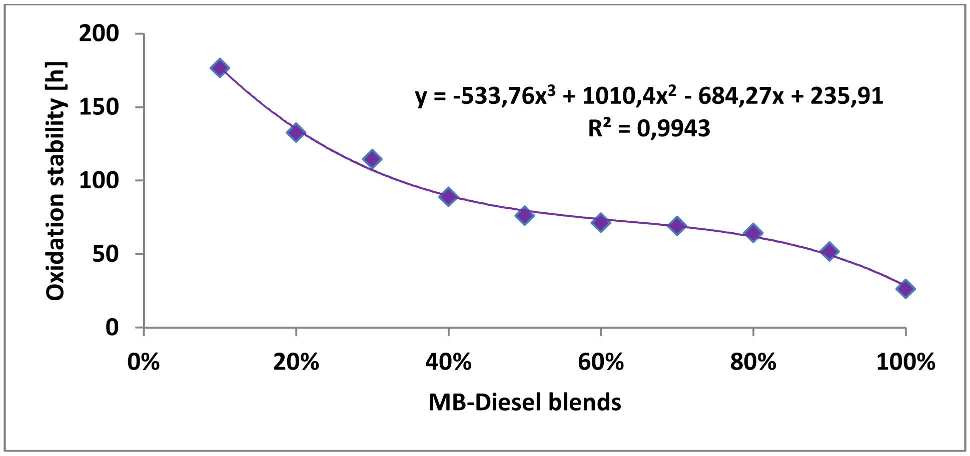
It can be observed that the coefficient of regression values show a high regression between Oxidation stability and biodiesel-diesel blends.



(a)



(b)



(c)

Figure 4.7: Effect of (a) PB-Diesel Blending (b) JB-Diesel Blending (c) MB-Diesel Blending on Oxidation Stability

4.3.1.6 Flash Point (FP)

Figure 4.8 (a-c) shows the correlations between flash points of PB, JB and MB and their blends with diesel. As can be seen, the flash points of PB, JB and MB increase with the increasing percentage of diesel in the blends. The flash points of PB, JB and MB and their blends with diesel were correlated using Polynomial Regression Analysis (PRA). The equations between flash point and blends ratio are:

For (PB-diesel blends):

$FP = 348.33x^3 - 370.63x^2 + 136.03x + 67.131$ $x \equiv$ (%PB-diesel blends) (4.19)

$R^2 = 0.9951$

For (JB-diesel blends):

$FP = 76.593x^3 - 2.3252x^2 + 39.32x + 72.209$ $x \equiv$ (%JB-diesel blends) (4.20)

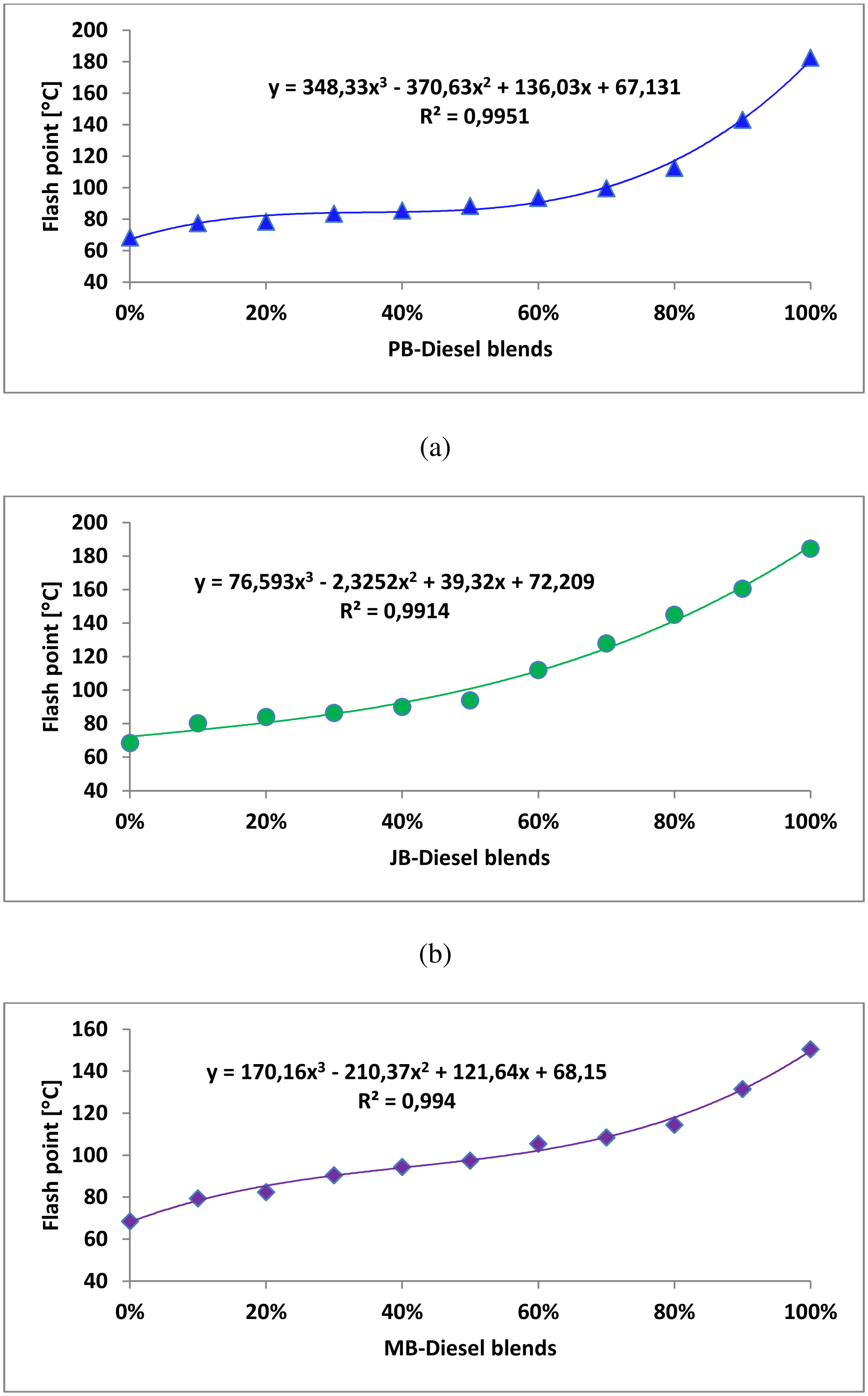
$R^2 = 0.9914$

For (MB-diesel blends):

$FP = 170.16x^3 - 210.37x^2 + 121.64x + 68.15$ $x \equiv$ (%MB-diesel blends) (4.21)

$R^2 = 0.994$

It can be observed that the coefficient of regression values show a high regression between Flash point and biodiesel-diesel blends.



(a)

(b)

(c)

Figure 4.8: Effect of (a) PB-Diesel Blending (b) JB-Diesel Blending (c) MB-Diesel Blending on Flash Point

4.4 Engine Performance Analysis

In this study, to evaluate the performance of biodiesel blends 3 sets of fuel **(Table 3.9)** were prepared. 1st set consists of diesel fuel (B0) and Palm biodiesel-diesel blends includes PB5, PB10, PB15 and PB20. 2nd set consists of diesel fuel (B0) and Jatropha biodiesel-diesel blends such as JB5, JB10, JB15 and JB20. 3rd consists of diesel fuel (BO) and *Moringa oleifera* biodiesel-diesel blends includes MB5, MB10, MB15 and MB20. In order to carry out engine performance tests, the engine was run at various speeds range from 1000 rpm to 4000 rpm at an interval of 500 rpm at full load condition. Engine test conditions were monitored by REO-DCA controller connected through a desktop to the engine test bed. Engine performance was evaluated in terms of engine torque, brake power (BP) and brake specific fuel consumption (BSFC). The engine was run with diesel fuel for several minutes to warm it up before biodiesel was tested. Likewise, the engine was operated with diesel fuel before it was shut down. The same procedure was used for each fuel test. The following section will discuss the obtained results of these parameters.

4.4.1 Engine Torque

The effect of Palm, *Jatropha curcas* and *Moringa oleifera* biodiesel and their blend with diesel fuel on the engine torque with respect to the engine speed are shown in Figures 4.9-4.11. Considering torque performance with all the fuel blends tested, it can be seen that the trend of these parameters as a function of speed is almost similar with diesel fuel. It can be seen that torque increases steadily with speed up to a maximum value, and then falls with further increases in speed. This is mainly attributed to two main reasons. The first reason is the mechanical friction loss, and the second is lower volumetric efficiency of the engine due to increasing speed. It is also clear that the torque is decreased slightly with the increasing percentages of biodiesel in the blend.

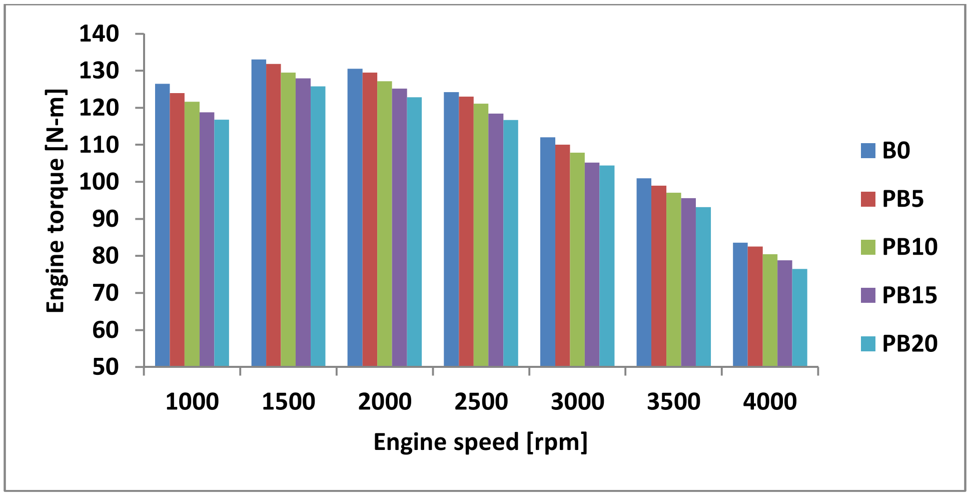


Figure 4.9: Torque versus Engine Speed for Palm Biodiesel Blended Fuel at Full Load Condition

Over the whole range of speed, for Palm biodiesel blended fuel, the average torque values were found 115.82, 114.25, 112.27, 109.98 and 108.02 N-m for the B0, PB5, PB10, PB15 and PB20 blends respectively. The fuel sample PB5, PB10, PB15 and PB20 blends gives an average reduction in torque of 1.35, 3.07, 5.04 and 6.73% respectively compared to that of diesel fuel over the entire range of speed.

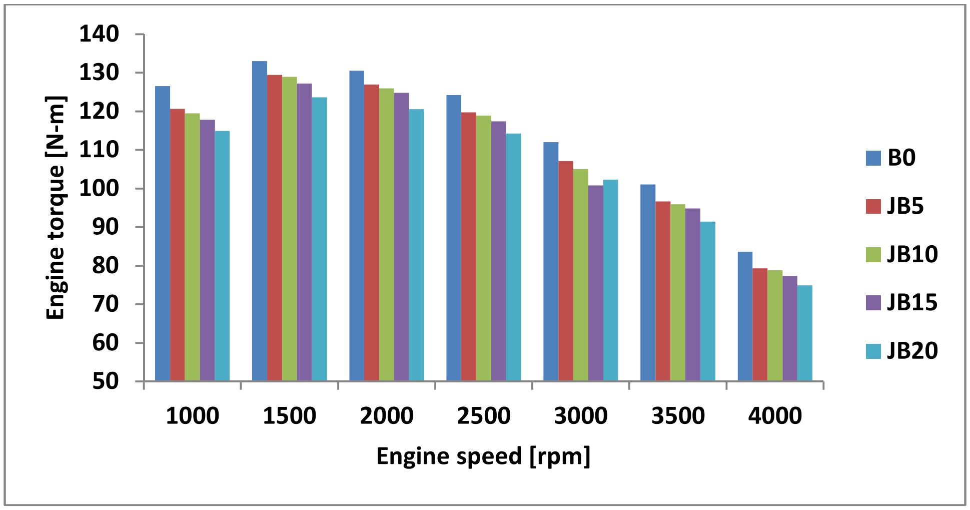


Figure 4.10: Torque versus Engine Speed for Jatropha Biodiesel Blended Fuel at Full Load Condition

For Jatropha biodiesel blended fuel, the average torque values were found 115.82, 113.37, 110.41, 108.38 and 105.97 N-m for the B0, JB5, JB10, JB15 and JB20 blends respectively. The fuel sample B0, JB5, JB10, JB15 and JB20 blends gives an average reduction in torque of 3.84, 4.67, 6.42 and 8.51% respectively compared to that of diesel fuel over the entire range of speed.

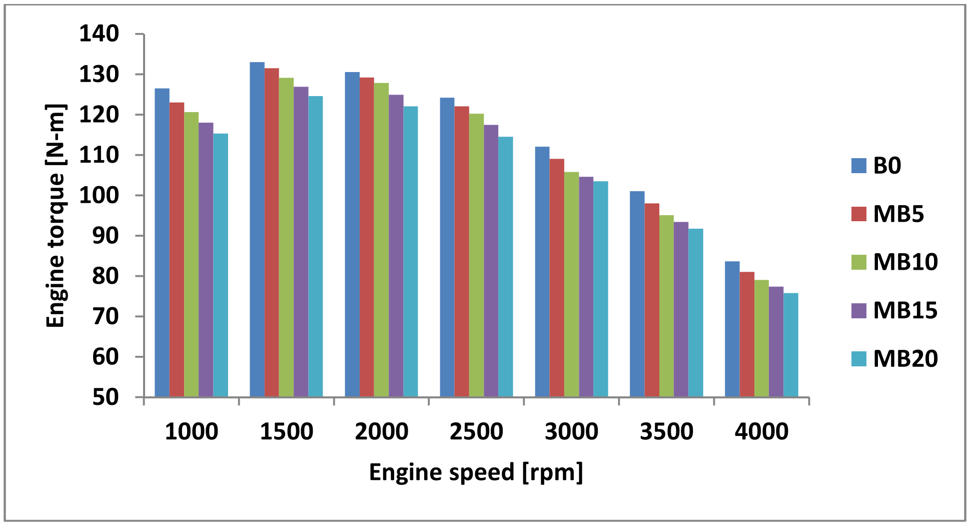


Figure 4.11: Torque versus Engine Speed for Moringa Biodiesel Blended Fuel at Full Load Condition

For Moringa biodiesel blended fuel, the average torque values were found 115.82, 113.38, 111.22, 109.12 and 106.77 N-m for the B0, MB5, MB10, MB15 and MB20 blends respectively. The fuel sample MB5, MB10, MB15 and MB20 blends gives an average reduction in torque of 2.10, 3.97, 5.78 and 7.81% respectively compared to diesel fuel over the entire range of speed.

It can be seen that the torque values are higher when diesel fuel is being used, which is supported by the literature (Murillo et al., 2007; Liaquat et al., 2012). The reason of reduction in torque with the diesel fuel can be attributed to the lower viscosity, density and higher calorific values of the diesel fuel. It has been reported that biodiesel have a major effect on the engine performance due to higher oxygen contents, higher viscosity and density, lower calorific values, higher cetane number and these factors influence on injection and combustion system (Özener et al., 2012).

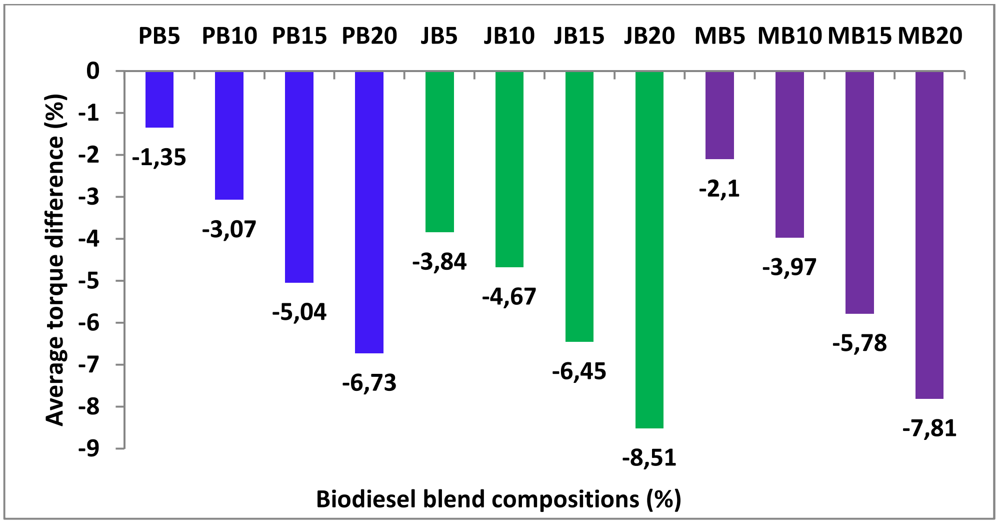


Figure 4.12: Average Torque Difference Compared to Diesel Fuel

It can be seen from the Figure 4.12 that the lowest average reduction in the torque values compared to diesel fuel was found for Palm biodiesel blended fuel followed by *Moringa oleifera* biodiesel and *Jatropha curcas* biodiesel blended fuel respectively. The reason can be explained that Palm biodiesel have lower viscosity, density and higher calorific value compared to *Moringa oleifera* and *Jatropha curcas* biodiesel.

4.4.2 Brake Power

The effect of Palm, *Jatropha curcas* and *Moringa oleifera* biodiesel and their blend with diesel fuel on the engine brake power with respect to the engine speed are shown in Figures

4.13-4.15. Considering brake power performance with all the fuel blends tested, it can be seen that the trend of these parameters as a function of speed is almost similar with diesel fuel. It can be seen that brake power increased steadily with engine speed until 3500 rpm then starts to decrease due to frictional force. It is also clear that brake power is decreased slightly with the increasing percentages of biodiesel in the blend.

Over the whole range of speed, for Palm biodiesel blended fuel, the average brake power values were found 28.72, 28.32, 27.81, 27.24 and 26.73 kW for the B0, PB5, PB10, PB15 and PB20 blends respectively. The fuel sample PB5, PB10, PB15 and PB20 blends gives an average reduction in brake power of 1.38, 3.16, 5.14 and 6.92% respectively compared to that of diesel fuel over the entire range of speed.

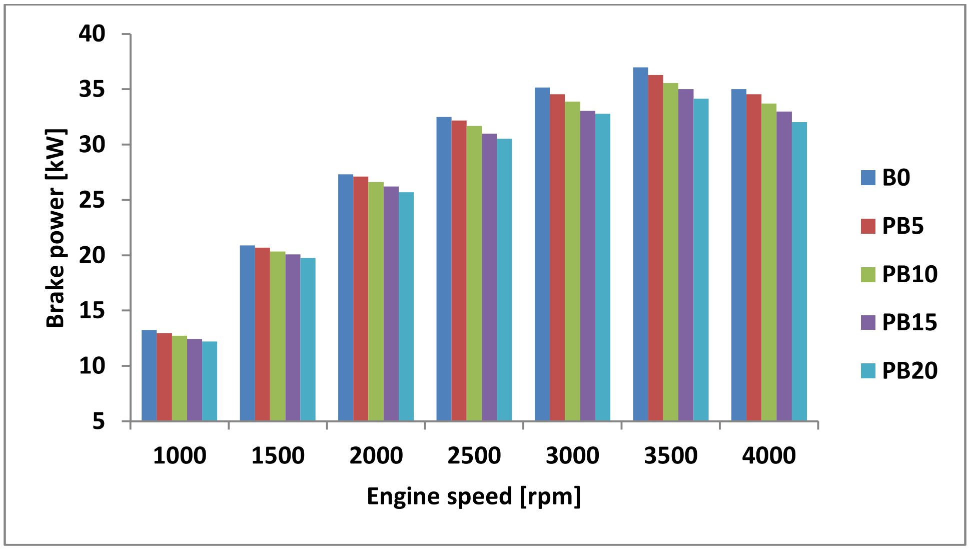


Figure 4.13: Brake Power versus Engine Speed for Palm Biodiesel Blended Fuel at Full Load Condition

For Jatropha biodiesel blended fuel, the average brake power values were found 28.72, 27.57, 27.32, 26.76 and 26.35 kW for the B0, JB5, JB10, JB15 and JB20 blends respectively. The fuel sample JB5, JB10, JB15 and JB20 blends gives an average reduction in brake power of 4.0, 4.86, 6.82 and 8.25% respectively compared to that of diesel fuel over the entire range of speed.

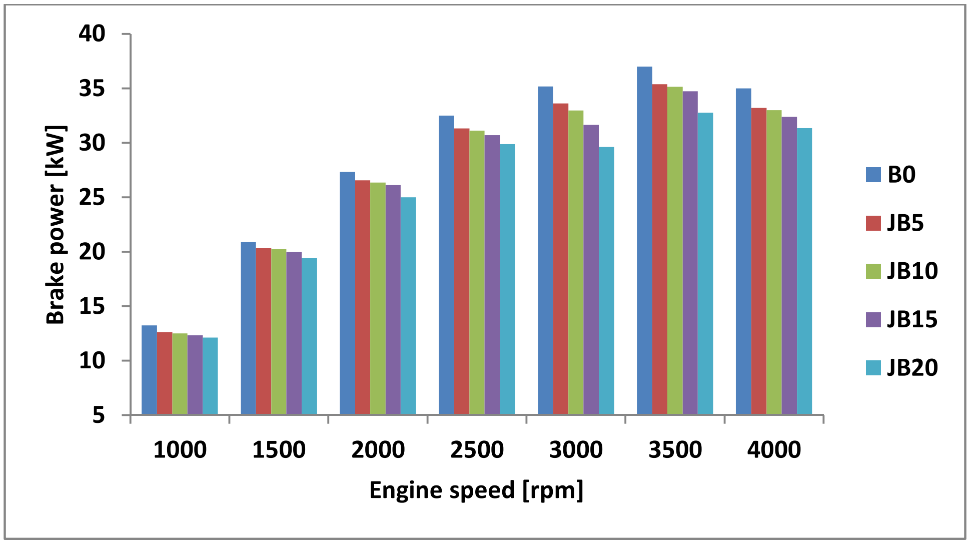


Figure 4.14: Brake Power versus Engine Speed for Jatropha Biodiesel Blended Fuel at Full Load Condition

For Moringa biodiesel blended fuel, the average brake power values were found 28.72, 28.07, 27.51, 27.0, and 26.41 kW for the B0, MB5, MB10, MB15 and MB20 blends respectively. The fuel sample MB5, MB10, MB15 and MB20 blends gives an average reduction in brake power of 2.27, 4.22, 5.97 and 8.03% compared to that of diesel fuel over the entire range of speed.

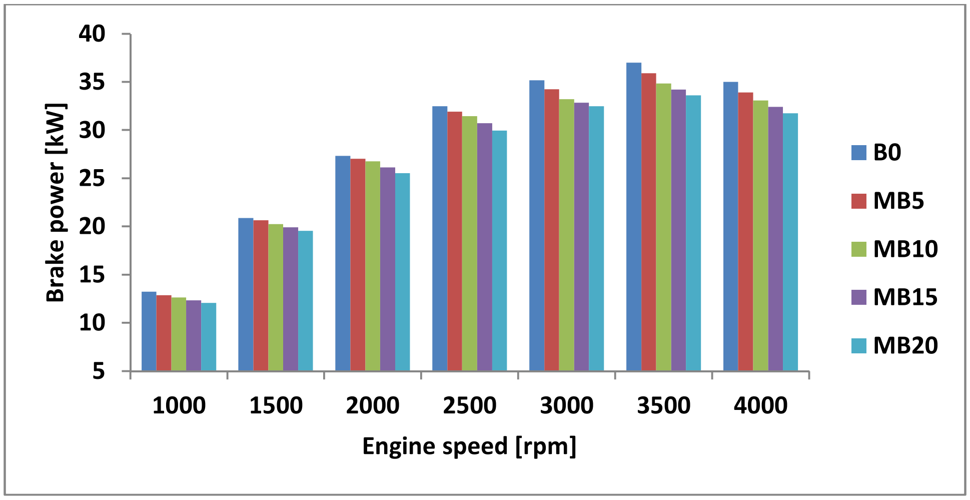


Figure 4.15: Brake Power versus Engine Speed for Moringa Biodiesel Blended Fuel at Full Load Condition

It can be seen that the brake power values are higher when diesel blended fuel is being used, which is supported by the literature (Shahabuddin et al., 2012). The reason for the higher brake power of biodiesels compared to diesel can be attributed to their higher calorific values and lower viscosities. Both the calorific value and viscosity have an effect on the engine combustion system. Additionally, uneven combustion characteristics of biodiesel fuel decreased the engine brake power (Muralidharan et al., 2011).

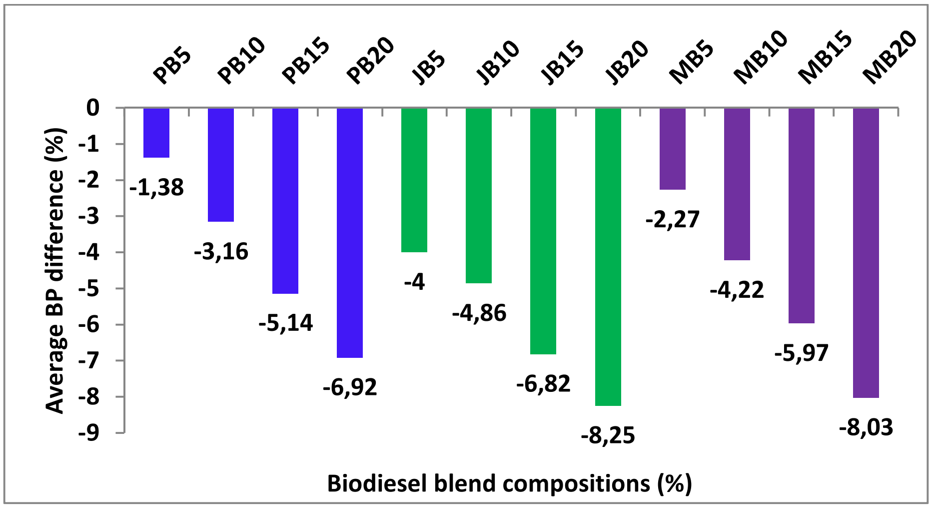


Figure 4.16: Average Brake Power Difference Compared to Diesel Fuel

It is seen from the Figure 4.16 that the lowest average reduction in the brake power values compared to diesel fuel was found for Palm biodiesel blended fuel followed by Moringa biodiesel and Jatropha biodiesel blended fuel respectively. The reason can be explained that Palm biodiesel have higher calorific value and lower viscosities than both Jatropha biodiesel and Moringa biodiesel.

4.4.3 Brake Specific Fuel Consumptions

BSFC is the ratio between mass flow of the tested fuel and effective power. The BSFC of diesel engine depends on the relationship among volumetric fuel injection system, fuel density, viscosity and lower heating value (Qi et al., 2010a). The effect of Palm, *Jatropha curcas* and *Moringa oleifera* biodiesel and their blend with diesel fuel on the engine brake specific fuel consumption with respect to the engine speed are shown in Figures 17-19. Considering brake specification fuel consumption performance with all the fuel blends tested, it can be seen that the trend of these parameters as a function of speed is almost similar with diesel fuel. Compared to diesel fuel the BSFC increased slightly with an increase in the biodiesel blend ratio.

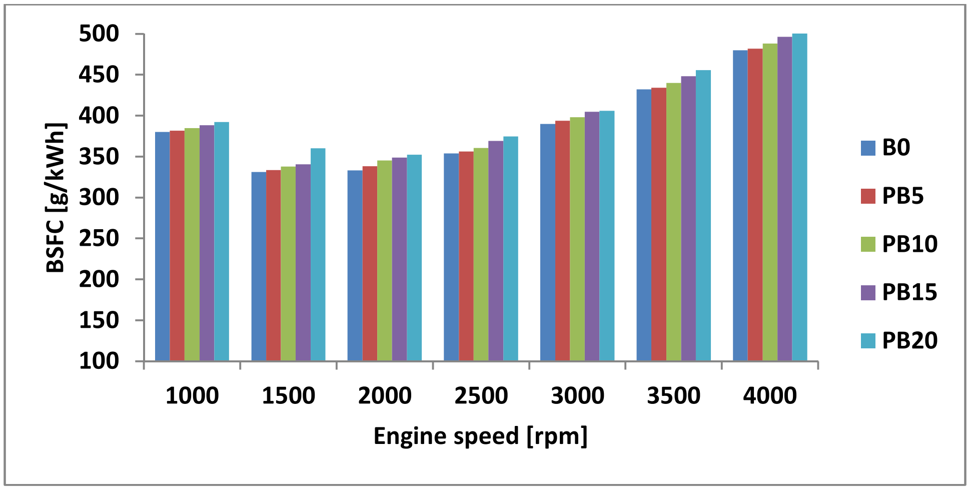


Figure 4.17: BSFC versus Engine Speed for Palm Biodiesel Blended Fuel at Full Load Condition

Over the whole range of speed, for Palm biodiesel blended fuel, the average brake specific fuel consumption values were found 385.71, 388.4, 393.54, 399.4 and 406.62 g/kWh for the B0, PB5, PB10, PB15 and PB20 blends respectively. The fuel sample PB5, PB10, PB15 and PB20 blends gives an average increase in brake specific fuel consumption of 0.69, 2.02, 3.54 and 5.42% respectively compared to that of diesel fuel over the entire range of speed.

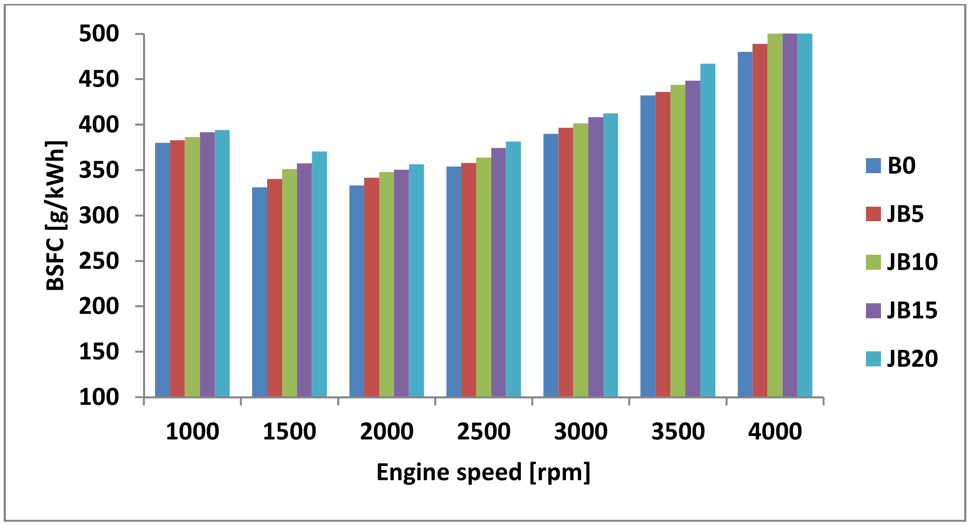


Figure 4.18: BSFC versus Engine Speed for Jatropha Biodiesel Blended Fuel at Full Load Condition

For Jatropha biodiesel blended fuel, the average brake specific fuel consumption values were found 385.71, 391.94, 399.18, 405.52 and 413.32 g/kWh for the B0, JB5, JB10, JB15 and JB20 blends respectively. The fuel sample JB5, JB10, JB15 and JB20 blends gives an average increase in brake specific fuel consumption of 1.61, 3.49, 5.13 and 7.15% respectively compared to that of diesel fuel over the entire range of speed.

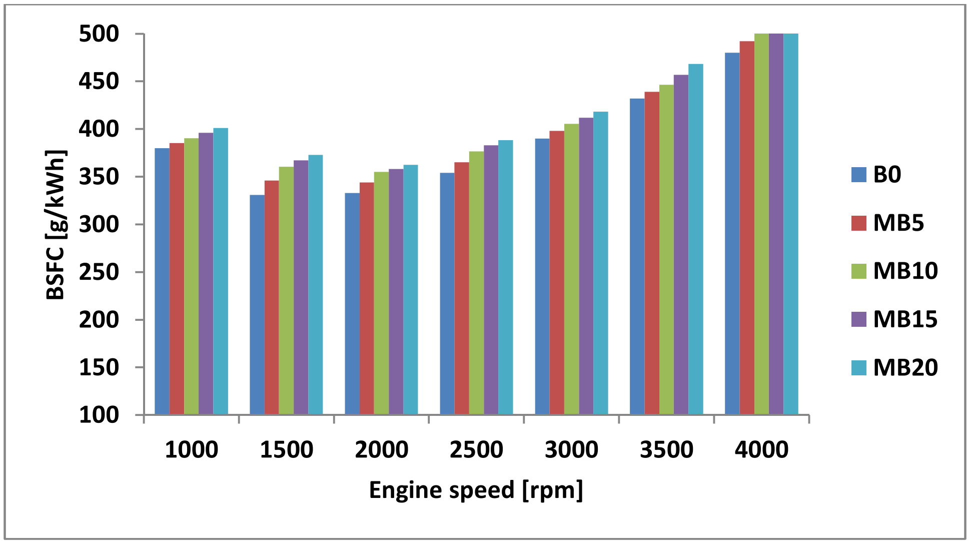


Figure 4.19: BSFC versus Engine Speed for Moringa Biodiesel Blended Fuel at Full Load Condition

For Moringa biodiesel blended fuel, the average brake specific fuel consumption values were found 385.71, 395.6, 405.51, 411.81, and 418.08 g/kWh for the B0, MB5, MB10, MB15 and MB20 blends respectively. The fuel sample MB5, MB10, MB15 and MB20 blends gives an average increase in brake specific fuel consumption of 2.56, 5.13, 6.76 and 8.39% respectively compared to that of diesel fuel over the entire range of speed.

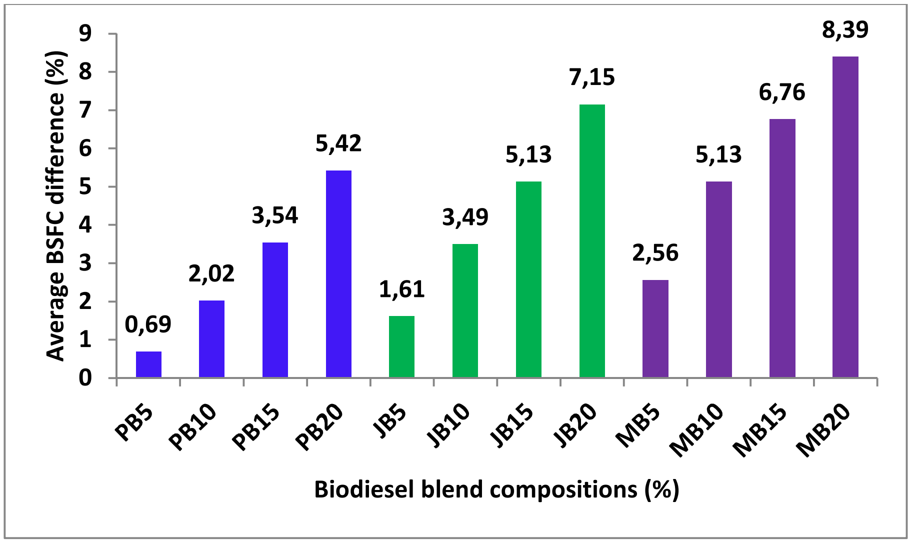


Figure 4.20: Average BSFC Difference Compared to Diesel Fuel

It can be seen that the brake specific fuel consumption values are lower when biodiesel blended fuel is being used, which is supported by the literature (Chauhan et al., 2012; Shahabuddin et al., 2012; Wang et al., 2013). The reason for the lower BSFC of diesels can be attributed to the effects of the lower density, viscosity and higher heating value of the diesel (Liaquat et al., 2012). On the other hand, biodiesel fuel is delivered into the engine on a volumetric basis per stroke; thus, larger quantities of biodiesel are fed into the engine. Therefore, to produce the same power, more biodiesel fuel is needed because biodiesel has a lower calorific value compared to diesel fuel (Tsolakis et al., 2007). It is seen from the Figure 4.20 that the average BSFC was found higher for Moringa biodiesel blend followed by Jatropha and palm biodiesel. The reason can be explained that the Moringa biodiesel have higher viscosity and density (Table 4.2) compared to the other biodiesel.

4.5 Engine Emissions Study

In order to examine emission characteristics of all fuel samples, a portable BOSCH exhaust gas analyser (model BEA-350) was used to measure the concentration of exhaust gases of the test engine. The exhaust gases emission of NO and HC was measured in ppm while CO and CO_2 in volume percent. In this research work, exhaust emission was measured at various speeds range from 1000 rpm to 4000 rpm at an interval of 500 rpm at full load conditions by inserting probe into the tail pipe.

4.5.1 Carbon Monoxide (CO) Emission

CO is produced as a result of the incomplete combustion of the fuel. If the combustion is complete, CO is converted into CO_2 (Gumus and Kasifoglu, 2010). If the combustion is incomplete due to shortage of air or due to low gas temperature, CO will be formed.

Mostly, some factors such as air-fuel ratio, engine speed, injection timing, injection pressure and type of fuels have an impact on CO emission (Gumus et al., 2012). The effect of Palm, *Jatropha curcas* and *Moringa oleifera* biodiesel and their blend with diesel fuel on the CO emission with respect to the engine speed are shown in Figures 4.21-4.23.

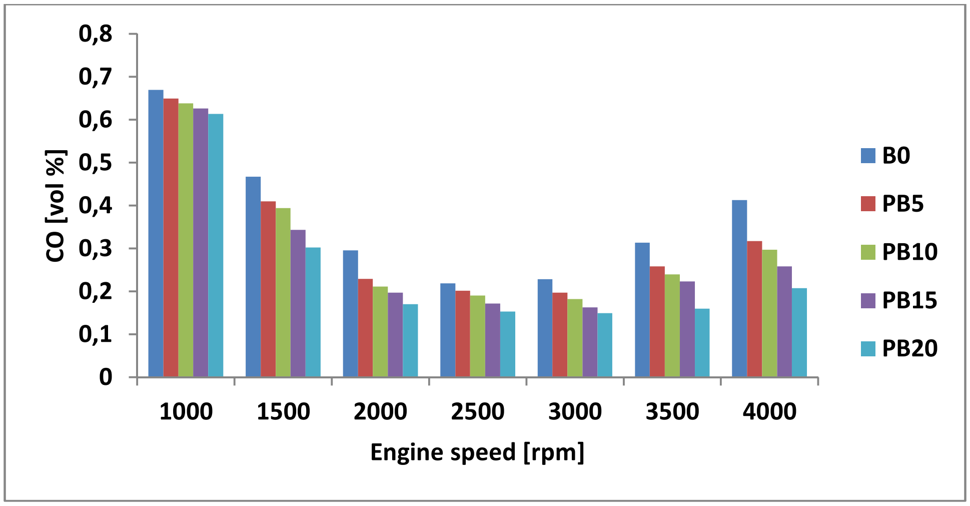


Figure 4.21: CO Emission versus Engine Speed for Palm Biodiesel Blended Fuel at Full Load Condition

Over the whole range of speed, for Palm biodiesel blended fuel, the average CO emissions were found 0.37, 0.32, 0.30, 0.28 and 0.25 vol% for the B0, PB5, PB10, PB15 and PB20 blends respectively. The fuel sample PB5, PB10, PB15 and PB20 blends gives an average reduction in CO emissions of 13.17, 17.36, 23.93, and 32.65% respectively compared to that of diesel fuel over the entire range of speed.

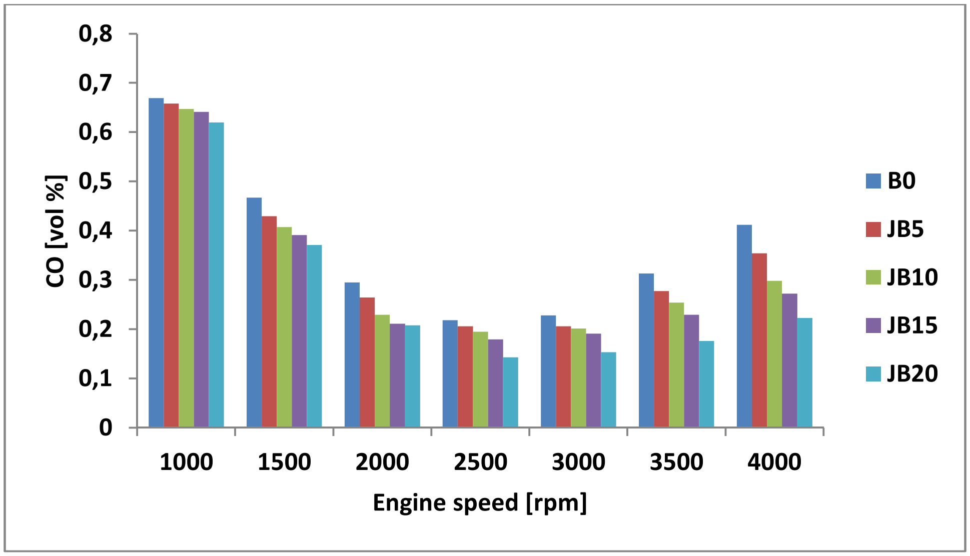


Figure 4.22: CO Emission versus Engine Speed for Jatropha Biodiesel Blended Fuel at Full Load Condition

For Jatropha biodiesel blended fuel, the average CO emissions were found 0.37, 0.34, 0.31, 0.30 and 0.27 vol% for the B0, JB5, JB10, JB15 and JB20 blends respectively. The fuel sample JB5, JB10, JB15 and JB20 blends gives an average reduction in CO emissions of 8.02, 14.29, 18.78, and 27.23% respectively compared to that of diesel fuel over the entire range of speed.

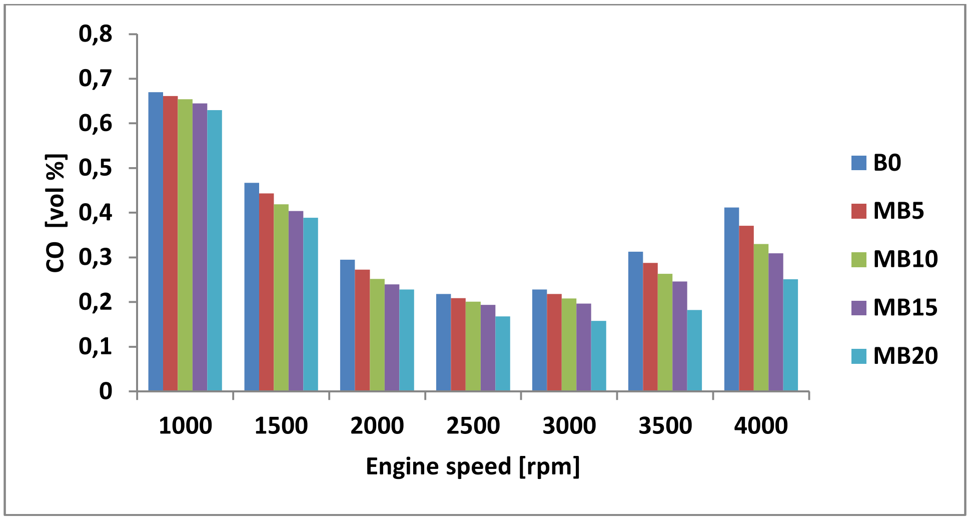


Figure 4.23: CO Emission versus Engine Speed for Moringa Biodiesel Blended Fuel at Full Load Condition

For Moringa biodiesel blended fuel, the average CO emissions were found 0.37, 0.35, 0.33, 0.31 and 0.28 vol% for the B0, MB 5, MB10, MB15 and MB20 blends respectively. The fuel sample MB5, MB10, MB15 and MB20 blends gives an average reduction in CO emissions of 5.37, 10.60, 14.13 and 22.93% compared to that of diesel fuel over the entire range of speed.

It can be seen that the CO emission values are lower when biodiesel blended fuel is being used, which is supported by the literature (Lapuerta et al., 2008; Rajaraman et al., 2009; Kim and Choi, 2010; Hirkude and Padalkar, 2012). This can be attributed to the higher oxygen contents and higher cetane number of biodiesel fuel. It is reported that biodiesel fuel contains 12% higher oxygen. As the percentage of biodiesel increased in the blend, the higher oxygen contents of biodiesel allow more carbon molecules to burn and combustion becomes completed. Thus CO emission is reduced in case of using biodiesel blend in a diesel engine. At higher engine speed, the variation of CO emission for biodiesel blended fuel is higher because higher cetane number of biodiesel makes combustion more complete at higher engine speed and load condition.

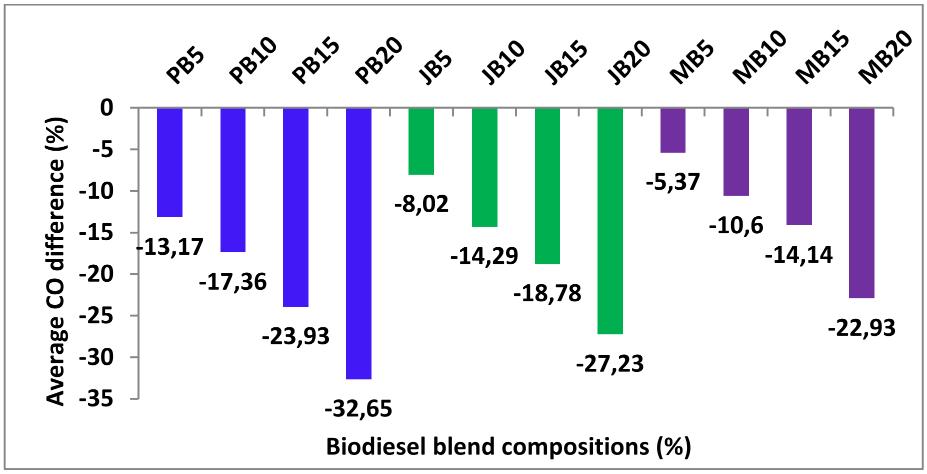


Figure 4.24: Average CO Emission Difference Compared to Diesel Fuel

It can be seen from the Figure 4.24 that the highest average reduction in the CO emission compared to diesel fuel was found for Palm biodiesel blended fuel followed by Jatropha and Moringa biodiesel blended fuel respectively. The reason can be explained by the degree of saturation of the fatty acids. It has been reported that CO emission is decreased as the saturation level is increased (Rodríguez et al., 2011). From the Table 4.3 it is seen that palm biodiesel have highest saturation level followed by Jatropha and Moringa biodiesel respectively. Moreover higher unsaturation level leads to higher density of the fuel. As the fuel delivery system is volumetric basis, therefore, palm biodiesel with their lower densities would restrict the formation of rich air-fuel mixture within the spray jet as compared to Jatropha and Moringa biodiesel blends fuel. This allows more complete combustion which helps to reduce CO emission (Ng et al., 2011).

4.5.2 Hydrocarbon (HC) Emission

Unburned HC is resulted from the incomplete combustion of fuel and flame quenching in the crevice regions in the cylinder wall. The HC emission also can be resulted from the problems of air and fuel mixing. The effect of Palm, *Jatropha curcas* and *Moringa oleifera* biodiesel and their blend with diesel fuel on the HC emission with respect to the engine speed are shown in Figures 4.25-4.27.

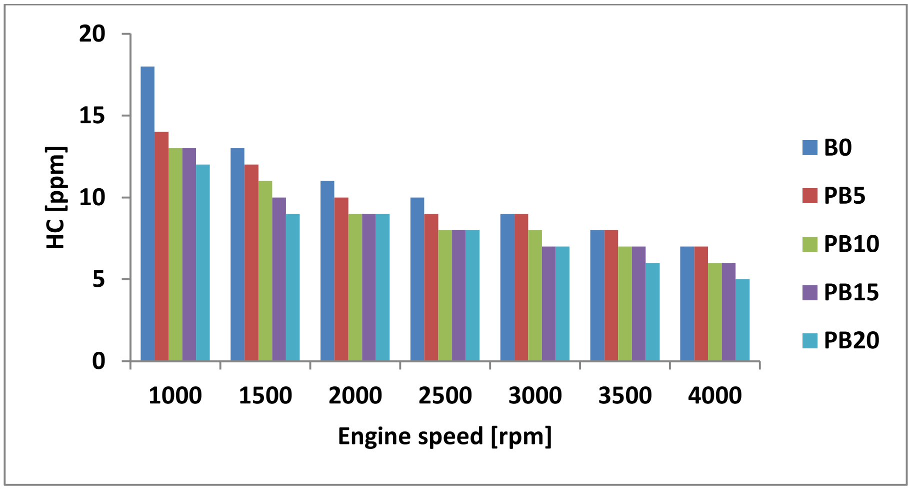


Figure 4.25: HC Emission versus Engine Speed for Palm Biodiesel Blended Fuel at Full Load Condition

Over the whole range of speed, for Palm biodiesel blended fuel, the average HC emission were found 10.85, 9.85, 8.85, 8.57, and 8 ppm for the B0, PB5, PB10, PB15 and PB20 blends respectively. The fuel sample PB5, PB10, PB15 and PB20 blends gives an average reduction in HC emission of 9.21, 18.42, 21.05 and 26.31% respectively compared to that of diesel fuel over the entire range of speed.

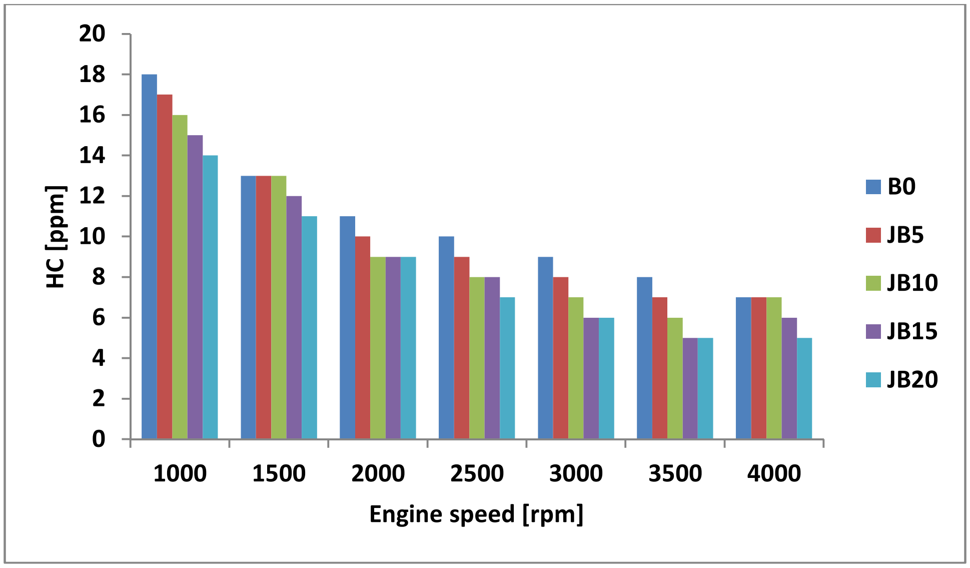


Figure 4.26: HC Emission versus Engine Speed for Jatropha Biodiesel Blended Fuel at Full Load Condition

For Jatropha biodiesel blended fuel, the average HC emission values were found 10.85, 10.14, 9.42, 8.71 and 8.14 ppm for the B0, JB5, JB10, JB15 and JB20 blends respectively. The fuel sample JB5, JB10, JB15 and JB20 blends gives an average reduction in HC emission of 6.57, 13.15, 19.73 and 25% respectively compared to that of diesel fuel over the entire range of speed.

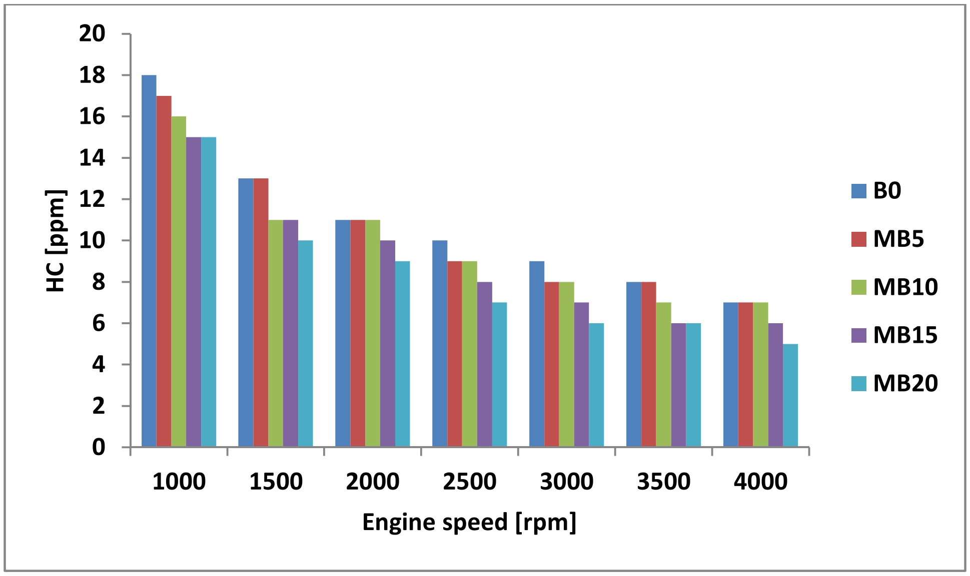


Figure 4.27: HC Emission versus Engine Speed for Moringa Biodiesel Blended Fuel at Full Load Condition

For Moringa biodiesel blended fuel, the average HC emission values were found 10.85, 10.42, 9.85, 9 and 8.28 ppm for the B0, MB5, MB10, MB15 and MB20 blends respectively. The fuel sample MB5, MB10, MB15 and MB20 blends gives an average reduction in HC emission of 3.94, 9.21, 17.10 and 23.68% respectively compared to that of diesel fuel over the entire range of speed.

It can be seen that the HC emission values are lower when biodiesel blended fuel is being used, which is supported by the literature (Özgünay et al., 2007; Ozsezen et al., 2009;

Ulusoy et al., 2009). This can be attributed to the higher oxygen contents and higher cetane number of biodiesel fuel. Biodiesel contains higher oxygen and lower carbon and hydrogen than diesel fuel which trigger an improved and complete combustion process (Lin et al., 2009; Qi et al., 2010b). Thus HC emission is reduced in case of using biodiesel blend in a diesel engine.

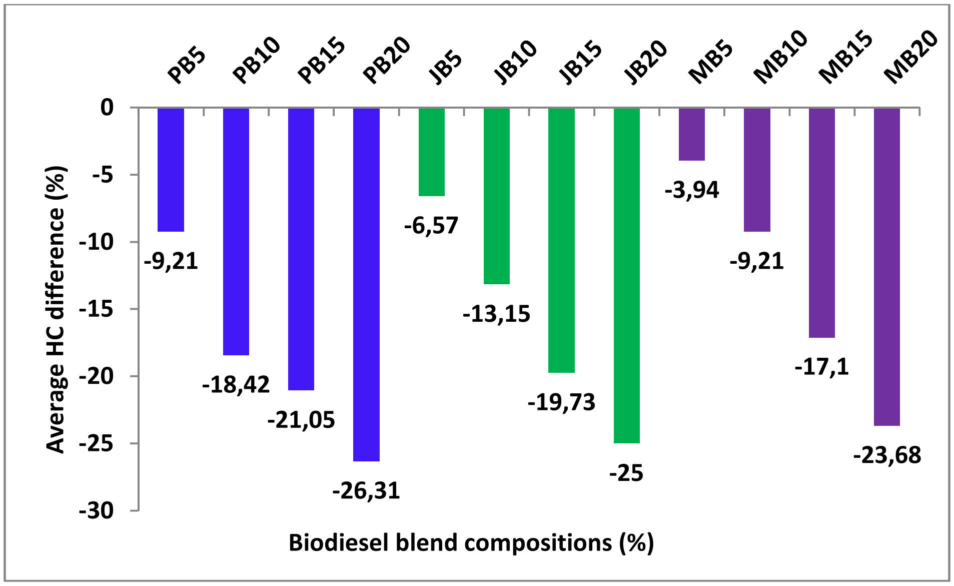


Figure 4.28: Average HC Emission Difference Compared to Diesel Fuel

It can be seen from the Figure 4.28 that the highest average reduction in the HC emission compared to diesel fuel was found for Palm biodiesel blended fuel followed by Jatropha and Moringa biodiesel blended fuel respectively. The reason can be explained by the highest degree of saturated fatty acids composition of Palm biodiesel which produced complete combustion compared to other biodiesel. It has also been reported that the higher cetane number of biodiesel fuel reduces the ignition delay which have an effect on the reduction of HC emission (Monyem and Gerpen, 2001; Rao, 2011). In this regard, from Table 4.2 it is clear that the Palm biodiesel have highest cetane number among the all biodiesel samples.

4.5.3 Nitric Oxide (NO) Emission

NOx is produced during the combustion process when nitrogen and oxygen are present at elevated temperatures. The oxides of nitrogen in the exhaust emissions contain nitric oxide (NO) and nitrogen dioxide (NO_2). The formation of NOx is highly dependent on in-cylinder temperatures, the oxygen concentration, and residence time for the reaction to take place (Xue et al., 2011). The increase in temperature and oxygen causes more NO_X to be produced. The effect of Palm, *Jatropha curcas* and *Moringa oleifera* biodiesel and their blend with diesel fuel on the NO emission with respect to the engine speed are shown in Figures 4.29-4.31.

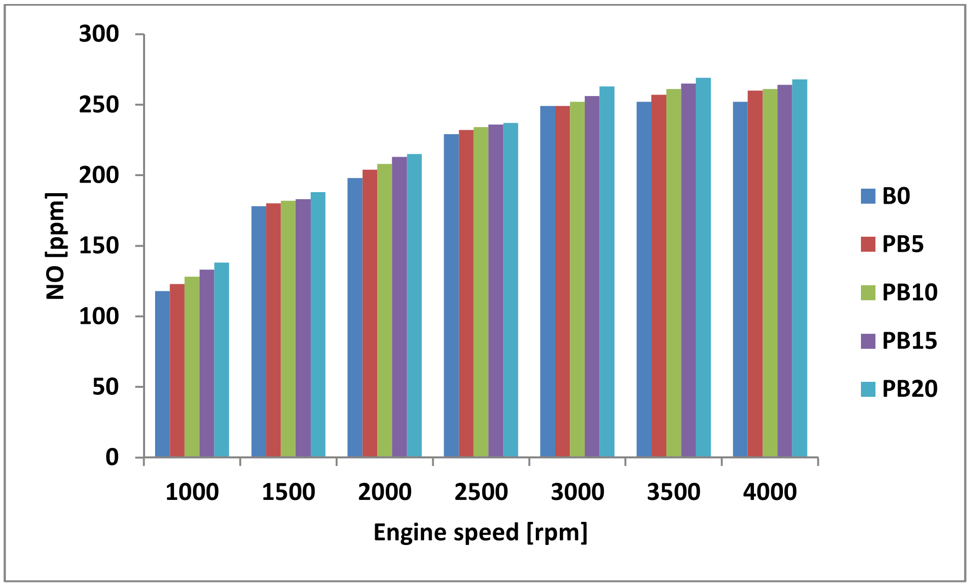


Figure 4.29: NO Emission versus Engine Speed for Palm Biodiesel Blended Fuel at Full Load Condition

Over the whole range of speed, for Palm biodiesel blended fuel, the average NO emission values were found 210.85, 215, 218, 221.42 and 225.42 ppm for the B0, PB5, PB10, PB15 and PB20 blends respectively. The fuel sample PB5, PB10, PB15 and PB20 blends gives an average increase in NO emission of 1.96, 3.38, 5.01 and 6.91% respectively compared to that of diesel fuel over the entire range of speed.

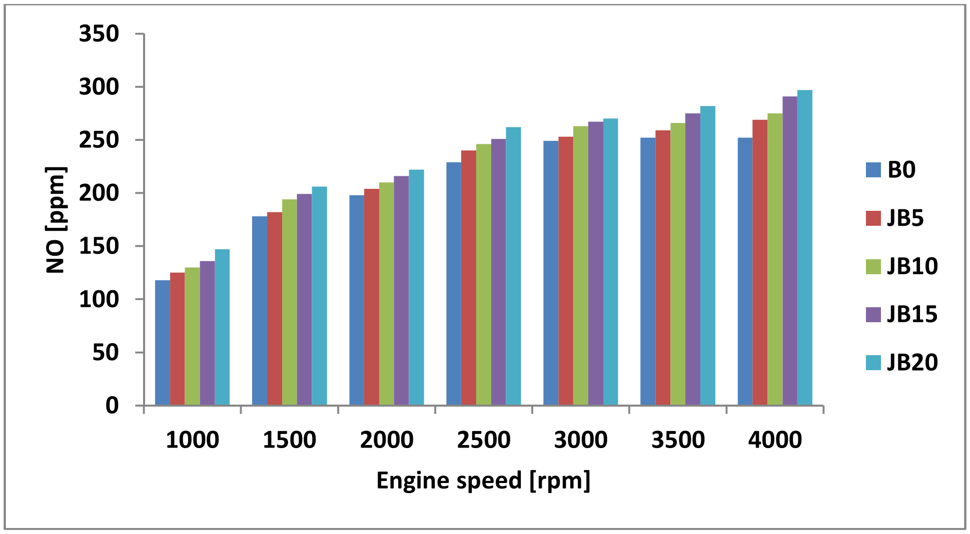


Figure 4.30: NO Emission versus Engine Speed for Jatropha Biodiesel Blended Fuel at Full Load Condition

For Jatropha biodiesel blended fuel, the average NO emission values were found 210.85, 218.85, 226.28, 233.57 and 240.85 ppm for the B0, JB 5, JB10, JB15 and JB20 blends respectively. The fuel sample JB5, JB10, JB15 and JB20 blends gives an average increase in NO emission of 3.79, 7.31, 10.76 and 14.22% compared to that of diesel fuel over the entire range of speed.

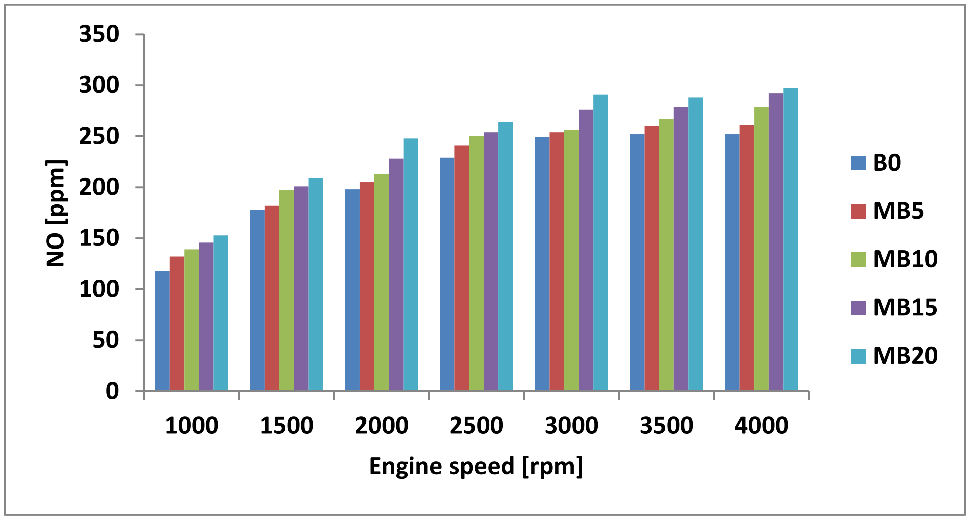


Figure4.31: NO Emission versus Engine Speed for Moringa Biodiesel Blended Fuel at Full Load Condition

For Moringa biodiesel blended fuel, the average NO emission values were found 210.85, 219.28, 228.71, 239.42 and 250 ppm for the B0, MB5, MB10, MB15 and MB20 blends respectively. The fuel sample MB5, MB10, MB15 and MB20 blends gives an average increase in NO emission of 3.99, 8.46, 13.55 and 18.56% compared to that of diesel fuel over the entire range of speed.

It can be seen that the NO emission values are higher when biodiesel blended fuel is being used. Same observation was observed in literature (El-Kasaby and Nemit-allah, 2013). This can be attributed to the bulk modulus of biodiesel, longer fuel penetration into the engine cylinder, decreased the radiative heat transfer due to reduced soot formation, shorter ignition delay and higher heat release rate. Thus NO emission is increased for biodiesel blend than that of diesel fuel. Moreover, the reason of increasing NO/NO_x can be explained in terms of adiabatic flame temperature. Biodiesel fuel contains higher percentages of unsaturated fatty acids that have higher adiabatic flame temperature which causes higher NO/NOx emission (El-Kasaby and Nemit-allah, 2013).

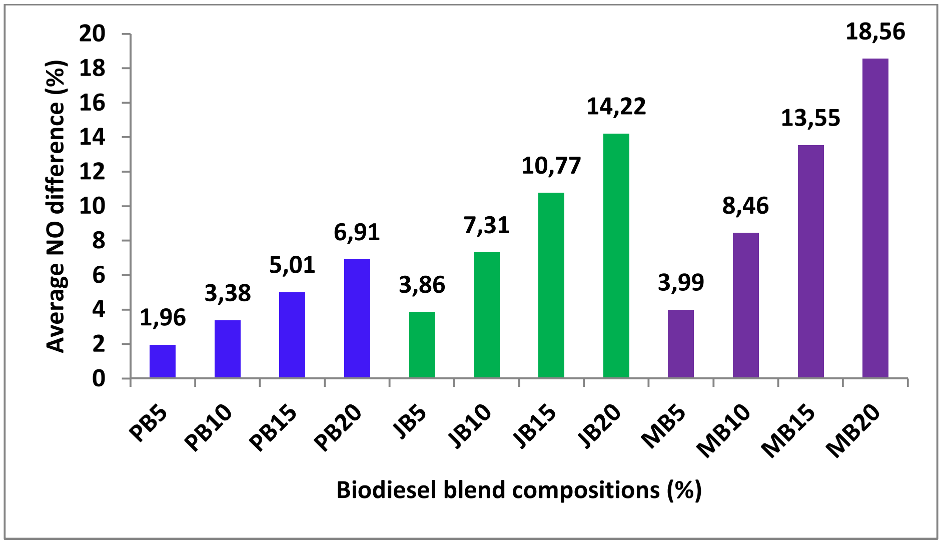


Figure 4.32: Average NO Emission Difference Compared to Diesel Fuel

It can be seen from the **Figure 4.32** that the average highest concentration of NO is produced from Moringa biodiesel blended fuel followed by Jatropha biodiesel and Palm biodiesel blended fuel respectively. The reason can be explained by the degree of unsaturated fatty acids composition. The presence of unsaturated fatty acids in the fuel reacts with N_2 and produces a NO through a reaction (Rao, 2011). In this regard it is clear from the Table 4.4 that Moringa biodiesel have highest percentages of unsaturated fatty acid followed by Jatropha biodiesel and Palm biodiesel respectively.

4.5.4 Carbon Dioxide Emission

CO_2 occurs naturally in the atmosphere and is a normal product of hydrocarbon fuel combustion. Ideally, combustion of a hydrocarbon fuel should produce only CO_2 and water (H_2O). The effect of Palm, Jatropha and Moringa biodiesel and their blend with diesel fuel on the CO_2 emission with respect to the engine speed are shown in Figures 4.33-4.35.

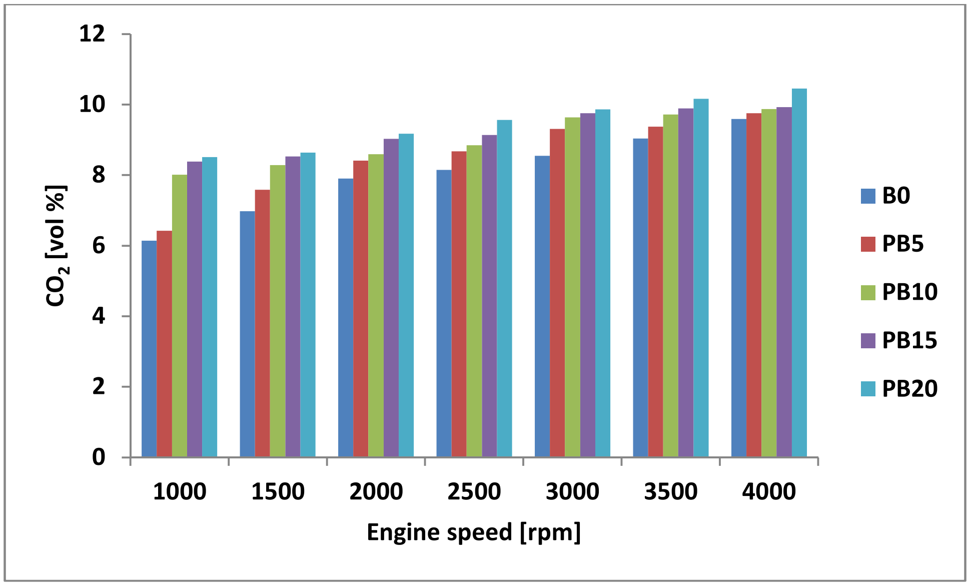


Figure 4.33: CO_2 Emission versus Engine Speed for Palm Biodiesel Blended Fuel at Full Load Condition

Over the whole range of speed, for Palm biodiesel blended fuel, the average CO_2 emission values were found 8.05, 8.50, 8.99, 9.23 and 9.47 vol% for the B0, PB 5, PB10, PB15 and PB20 blends respectively. The fuel sample PB5, PB10, PB15 and PB20 blends gives an average increase in CO_2 emission of 5.60, 11.73, 14.72 and 17.76% respectively compared to that of diesel fuel over the entire range of speed.

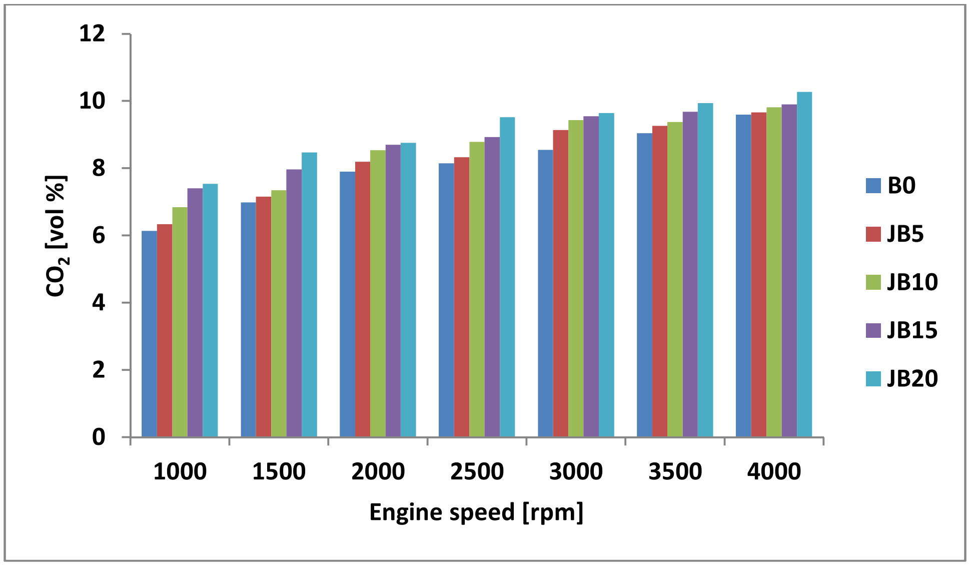


Figure 4.34: CO_2 Emission versus Engine Speed for Jatropha Biodiesel Blended Fuel at Full Load Condition

For Jatropha biodiesel blended fuel, the average CO_2 emission values were found 8.05, 8.29, 8.59, 8.87 and 9.16 vol% for the B0, JB5, JB10, JB15 and JB20 blends respectively. The fuel sample JB5, JB10, JB15 and JB20 blends gives an average increase in CO_2 emission of 3.07, 6.70, 10.25 and 13.82% respectively compared to that of diesel fuel over the entire range of speed.

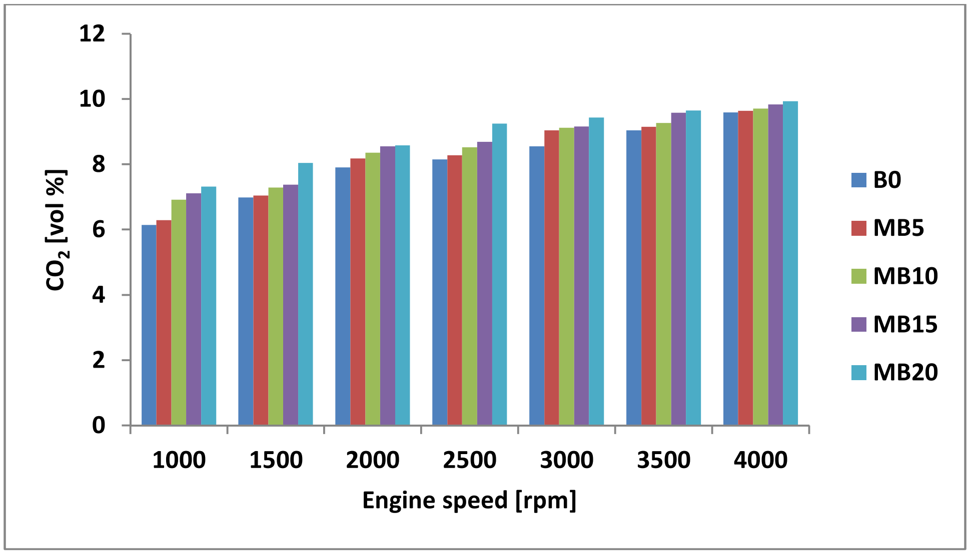


Figure 4.35: CO$_2$ Emission versus Engine Speed for Moringa Biodiesel Blended Fuel at Full Load Condition

For Moringa biodiesel blended fuel, the average CO$_2$ emission values were found 8.05, 8.23, 8.45, 8.61 and 8.88 vol% for the B0, MB5, MB10, MB15 and MB20 blends respectively. The fuel sample MB5, MB10, MB15 and MB20 blends gives an average increase in CO$_2$ emission of 2.25, 4.96, 6.99 and 10.36% respectively compared to that of diesel fuel over the entire range of speed.

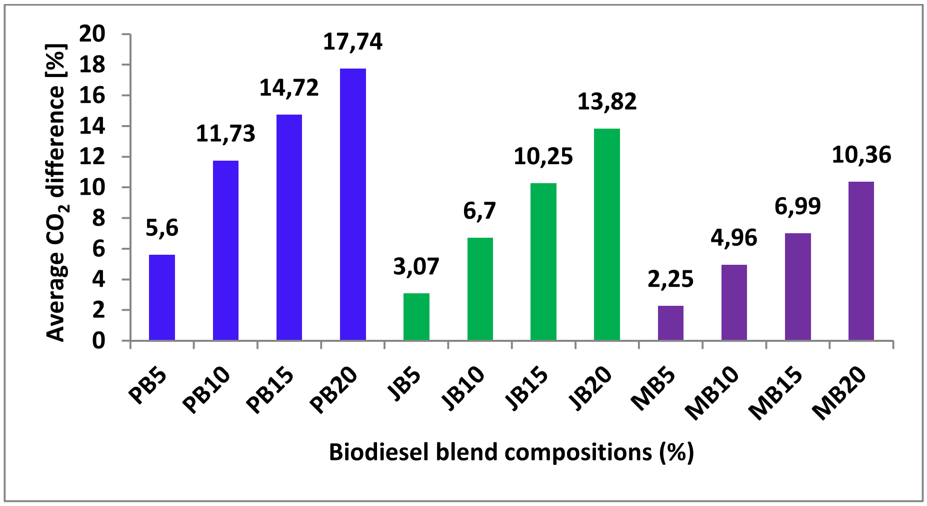


Figure 4.36: Average CO$_2$ Emission Difference Compared to Diesel Fuel

It can be seen that the CO_2 emission values are higher when biodiesel blended fuel is being used. It is also seen that CO_2 emission also increases as the percentages of biodiesel increases in the blend. This is happened due to the higher oxygen contents in the biodiesel fuel which improves the quality of combustion (Gumus and Kasifoglu, 2010). Moreover, from Figure 4.36 it can be observed that highest value of CO_2 emission was obtained when engine is fuelled with Palm biodiesel blended fuel followed by Jatropha biodiesel and Moringa biodiesel blended fuel. The reason can be explained by the highest degree of saturated fatty acids composition of Palm biodiesel which produced complete combustion compared to other biodiesel. Thus higher CO_2 emission is obtained. The production of CO_2 from the combustion of fossil fuels causes many environmental problems such as the accumulation of CO_2 in the atmosphere. Although biofuel combustion produces CO_2, absorption by crops helps to maintain CO_2 levels (Ramadhas et al., 2005). Therefore, biodiesel combustion can be regarded as definitely causing lower net CO_2 emission than diesel fuel.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

5.0 Conclusions

The main objective of this research work is to study the potential of biodiesel production from Palm (*Elaeis guineensis*), *Jatropha curcas* and *Moringa oleifera* oil as a promising feedstock that are easily accessible in many parts of the world. Series of experiment were sequentially conducted in this research to characterize the physical and chemical properties of Palm, *Jatropha curcas* and *Moringa oleifera* biodiesel and their 10% to 90% by volume blends such as kinematic viscosity, density, flash point, cloud point, pour point, cold filter plugging point, viscosity index and oxidation stability. Finally, a total of 12 fuel samples (B5 to B20 of each biodiesel) were used to evaluate their performance in an unmodified multi-cylinder diesel engine and compared with that of diesel fuel. Based on this research work, the following conclusion could be drawn:

1. The properties of Palm, *Jatropha curcas* and *Moringa oleifera* and their blends such as kinematic viscosity (KV), density (D), viscosity index (VI), cloud point (CP), pour point (PP), cold filter plugging point (CFPP), flash point (FP), calorific value (CV) and oxidation stability (OS) agree with ASTM D6751 and EN14214 standards.

2. Due to the blending of biodiesel with diesel fuel, the key fuel properties such as kinematic viscosity, density, calorific value and oxidation stability are remarkably

improved. Nevertheless, flash point and viscosity index decrease as the percentage of diesel increases in the blend.

3. Engine performance results show that engine torque and brake power for biodiesel blended fuels decreased compared to diesel fuel due to their higher density, viscosity and lower calorific value. The highest average reduction in torque and brake power compared to diesel fuel was found for Palm biodiesel followed by Moringa and Jatropha biodiesel blended fuels respectively.

4. The BSFC values for biodiesel blended fuels were higher compared to that of diesel fuel due to their lower calorific value and density. Among all biodiesel blended fuels, Moringa biodiesel blended fuel showed the highest average BSFC followed by Jatropha and Palm biodiesel blended fuels.

5. In case of engine emission test, a reduction in CO and HC emissions was found for biodiesel blended fuels compared to that of diesel fuel. The highest average reduction in CO and HC was found for Palm biodiesel blended fuel followed by Jatropha and Moringa biodiesel blended fuels due to the availability of saturated fatty acids composition in the fuels.

6. An increase in NO and CO_2 emissions was found for biodiesel blended fuels compared to that of diesel fuel due to their higher oxygen contents, saturated fatty acids, cetane number, in cylinder temperature and pressure etc.

In conclusion, Palm, *Jatropha curcas* and *Moringa oleifera* are potential feedstock for biodiesel production, and up to 20% of their blends can replace diesel fuel without modifying engines to reduce dependency on petro-diesel and produce cleaner exhaust emissions. Among these three feedstock Palm biodiesel showed better performance and emission characteristics.

5.1 Recommendations for Future Work

This research work has been carried out to produce biodiesel from available feedstocks and to evaluate the performance of biodiesel-diesel blends in a diesel engine. In this regard, the following recommendations for the future work can be suggested:

1. This research work only focused on engine performance and emission, so it is recommended to focus on combustion characteristics of biodiesel blended fuels in a diesel engine along with corrosion, wear and material compatibility studies.

2. In this research work up to 20% by volume blend of biodiesel was used, it is recommended to use higher percentages blends and then compare the findings with lower blends.

3. In this research work, only regulated emissions were studied, it is recommended to focus on unregulated emissions to get more insight on human health and environmental effect.

REFERENCES

Atabani, A. E., Silitonga, A. S., Ong, H. C., Mahlia, T. M. I., Masjuki, H. H., Badruddin, I. A., and Fayaz, H. (2013). Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renewable and Sustainable Energy Reviews **18** (0), 211-245.

Atadashi, I. M., Aroua, M. K., Abdul Aziz, A. R., and Sulaiman, N. M. N. (2012). Production of biodiesel using high free fatty acid feedstocks. Renewable and Sustainable Energy Reviews **16** (5), 3275-3285.

Atadashi, I. M., Aroua, M. K., and Aziz, A. A. (2010). High quality biodiesel and its diesel engine application: A review. Renewable and Sustainable Energy Reviews **14** (7), 1999-2008.

Aydin, H., and Bayindir, H. (2010). Performance and emission analysis of cottonseed oil methyl ester in a diesel engine. Renewable Energy **35** (3), 588-592.

Ayob, R., Sarpin, Z., and Hitam, A. (1998). Bench test of single-cylinder elsbett engine. In Proceeding of the PORIM international biofuel and lubricant conferences.

Azam, M. M., Waris, A., and Nahar, N.M. (2005). Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. Biomass and Bioenergy **29** (4), 293-302.

Balat, M. and Balat, H. (2010). Progress in biodiesel processing. Applied Energy **87** (6), 1815-1835.

Ban-Weiss, G. A., Chen, J. Y., Buchholz, B. A., and Dibble, R. W. (2007). A numerical investigation into the anomalous slight NOx increase when burning biodiesel; A new (old) theory. Fuel Processing Technology **88** (7), 659-667.

BP Statistical Review of World Energy June (2012). Available from: http://www.bp.com/assets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2012/STAGING/local_assets/pdf/statistical_review_of_world_energy_full_report_2012.pdf

Chapagain, B. P., Yehoshua, Y., and Wiesman, Z. (2009). Desert date (Balanites aegyptiaca) as an arid lands sustainable bioresource for biodiesel. Bioresource Technology **100** (3), 1221-1226.

Chauhan, B. S., Kumar, N., and Cho, H. M. (2012). A study on the performance and emission of a diesel engine fueled with Jatropha biodiesel oil and its blends. Energy **37** (1), 616-622.

Chauhan, B. S., Kumar, N., Du Jun, Y., and Lee, K. B. (2010). Performance and emission study of preheated Jatropha oil on medium capacity diesel engine. Energy **35** (6), 2484-2492.

Chin, M. (2011). Biofuels in Malaysia: an analysis of the legal and institutional framework. Working Paper 64. CIFOR, Bogor, Indonesia.

Demirbas, A. (2007). Importance of biodiesel as transportation fuel. Energy Policy **35** (9), 4661-4670.

Demirbas, A. (2008). Biodiesel: a realistic fuel alternative for diesel engines.London. Springer.

Demirbas, A. H., and Demirbas, I. (2007). Importance of rural bioenergy for developing countries. Energy Conversion and Management **48** (8), 2386-2398.

Devan, P. K., and Mahalakshmi, N.V. (2009a). Study of the performance, emission and combustion characteristics of a diesel engine using poon oil-based fuels. Fuel Processing Technology **90** (4), 513-519.

Devan, P. K., and Mahalakshmi, N.V. (2009b). Utilization of unattended methyl ester of paradise oil as fuel in diesel engine. Fuel **88** (10), 1828-1833.

da Silva, J. P. V., Serra, T. M., Gossmann, M., Wolf, C. R., Meneghetti, M. R., & Meneghetti, S. M. P. (2010). Moringa oleifera oil: Studies of characterization and biodiesel production. Biomass and Bioenergy, 34(10), 1527-1530.

DOE (2010). Environmental Quality Report. Department of Environment, Malaysia.

Dompok, B. G. (2010). The use of palm biodiesel by Sime Darby vehicles. Speech by Y.B. Tan Sri Bernard Giluk Dompok, Minister of Plantation Industries and Commodities, 24 March 2010. Carey Island, Selangor, Malaysia.

Ekrem, B. (2010). Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics. Fuel **89** (10), 3099-3105.

El-Kasaby, M. and Nemit-allah, M. A. (2013). Experimental investigations of ignition delay period and performance of a diesel engine operated with Jatropha oil biodiesel. Alexandria Engineering Journal **52** (2), 141-149.

United States Energy Information Administration (2010). [Cited 2012, 10th December]; Available from: http://www.indexmundi.com/energy.aspx?region=xx&product=biodiesel&graph=production+consumption.

Faiz, A., Sinha K., Walsh, M., and Varma A. 1990. Automotive Air Pollution: Issues and Options for Developing Countries. The World Bank.

Georgogianni, K. G., Katsoulidis, A. K., Pomonis, P. J., Manos, G., and Kontominas, M. G. (2009). Transesterification of rapeseed oil for the production of biodiesel using homogeneous and heterogeneous catalysis. Fuel Processing Technology **90** (7–8), 1016-1022.

Gumus, M. (2010). A comprehensive experimental investigation of combustion and heat release characteristics of a biodiesel (hazelnut kernel oil methyl ester) fueled direct injection compression ignition engine. Fuel **89** (10), 2802-2814.

Gumus, M., and Kasifoglu, S. (2010). Performance and emission evaluation of a compression ignition engine using a biodiesel (apricot seed kernel oil methyl ester) and its blends with diesel fuel. Biomass and Bioenergy **34** (1), 134-139.

Gumus, M., Sayin, C., and Canakci, M. (2012). The impact of fuel injection pressure on the exhaust emissions of a direct injection diesel engine fueled with biodiesel–diesel fuel blends. Fuel **95** (0), 486-494.

Hirkude, J. B., and Padalkar, A.S. (2012). Performance and emission analysis of a compression ignition: Engine operated on waste fried oil methyl esters. Applied Energy **90** (1), 68-72.

Hoekman, S. K., Broch, A., Robbins, C., Ceniceros, E., and Natarajan, M. (2012). Review of biodiesel composition, properties, and specifications. Renewable and Sustainable Energy Reviews **16** (1), 143-169.

How, H. G., Teoh, Y. H., Masjuki, H. H., and Kalam, M. A. (2012). Impact of coconut oil blends on particulate-phase PAHs and regulated emissions from a light duty diesel engine. Energy **48** (1), 500-509.

Huang, J., Wang, Y., Qin, J.-b., & Roskilly, A. P. (2010). Comparative study of performance and emissions of a diesel engine using Chinese pistache and jatropha biodiesel. Fuel Processing Technology, 91(11), 1761-1767.

International Energy Agency (IEA). Worl Energy Outlook (2012). [cited 2012 10th December]; Available from: http://www.worldenergyoutlook.org/publications/weo-2012/

Jain, S. and Sharma, M. P. (2010). Biodiesel production from *Jatropha curcas* oil. Renewable and Sustainable Energy Reviews **14** (9), 3140-3147.

Jain, S. and Sharma, M. P. (2011). Oxidation stability of blends of Jatropha biodiesel with diesel. Fuel **90** (10), 3014-3020.

Jia, L. W., Shen, M. Q., Wang, J., and Lin, M. Q. (2005). Influence of ethanolegasoline blended fuel on emission characteristics from a four-stroke motorcycle engine. Journal of Hazardous Materials **123** (1-3), 29-34.

Leevijit, T., & Prateepchaikul, G. (2011). Comparative performance and emissions of IDI-turbo automobile diesel engine operated using degummed, deacidified mixed crude palm oil–diesel blends. Fuel, 90(4), 1487-1491.

Kafuku, G., & Mbarawa, M. (2010). Alkaline catalyzed biodiesel production from Moringa oleifera oil with optimized production parameters. Applied Energy, 87(8), 2561-2565.

Karavalakis, G., Alvanou, F., Stournas, S., & Bakeas, E. (2009). Regulated and unregulated emissions of a light duty vehicle operated on diesel/palm-based methyl ester blends over NEDC and a non-legislated driving cycle. Fuel, 88(6), 1078-1085.

Kim, H. and Choi, B. (2010). The effect of biodiesel and bioethanol blended diesel fuel on nanoparticles and exhaust emissions from CRDI diesel engine. Renewable Energy **35** (1), 157-163.

Knothe, G. (2001). Historical perspectives on vegetable oil-based diesel fuels. Inform **11**, 1103-1107.

Lapuerta, M., Armas, O., and Rodríguez-Fernández, J. (2008). Effect of biodiesel fuels on diesel engine emissions. Progress in Energy and Combustion Science **34** (2), 198-223.

Lee, H. V., Taufiq-Yap, Y. H., Hussein, M. Z., and Yunus, R. (2013). Transesterification of jatropha oil with methanol over Mg–Zn mixed metal oxide catalysts. Energy **49** (0), 12-18.

Liaquat, A. M., Kalam, M. A., Masjuki, H. H., and Jayed, M. H. (2010). Potential emissions reduction in road transport sector using biofuel in developing countries. Atmospheric Environment **44** (32), 3869-3877.

Liaquat, A. M., Masjuki, H. H., Kalam, M. A., Varman, M., Hazrat, M. A., Shahabuddin, M., and Mofijur, M. (2012). Application of blend fuels in a diesel engine. Energy Procedia **14** (0), 1124-1133.

Lim, S. and Teong, L. K. (2010). Recent trends, opportunities and challenges of biodiesel in Malaysia: An overview. Renewable and Sustainable Energy Reviews **14** (3), 938-954.

Lin, B.-F., Huang, J.-H., and Huang, D.-Y. (2009). Experimental study of the effects of vegetable oil methyl ester on DI diesel engine performance characteristics and pollutant emissions. Fuel **88** (9), 1779-1785.

Lin, L., Cunshan, Z., Vittayapadung, S., Xiangqian, S., and Mingdong, D. (2011). Opportunities and challenges for biodiesel fuel. Applied Energy **88** (4), 1020-1031.

Lopez, G. P. and Laan, T. (2008). Biofuels—at what cost? Government support for biodiesel in Malaysia. Prepared for the Global Subsidies Initiative (GSI) of the International Institute for Sustainable Development (IISD). Geneva, Switzerland.

Malaysia Palm Oil Board (MPOB)a (2010). Available from: http://econ.mpob.gov.my/economy/biodiesel/biodiesel_plant.pdf

M Palash, S., Kalam, M. A., Masjuki, H. H., Masum, B. M., Rizwanul Fattah, I. M., and Mofijur, M. (2013). Impacts of biodiesel combustion on NOx emissions and their reduction approaches. Renewable and Sustainable Energy Reviews **23** (0), 473-490.

Mallikappa, D. N., Reddy, R. P., and Murthy, C. S. N. (2012). Performance and emission characteristics of double cylinder CI engine operated with cardanol bio fuel blends. Renewable Energy **38** (1), 150-154.

Monyem, A. and Gerpen, J. (2001). The effect of biodiesel oxidation on engine performance and emissions. Biomass and Bioenergy **20** (4), 317-325.

Moser, B. (2009). Biodiesel production, properties, and feedstocks. In Vitro Cell Dev Biol-Plant **45**, 229–266.

Mrad, N., Varuvel, E.G., Tazerout, M., and Aloui, F. (2012). Effects of biofuel from fish oil industrial residue-Diesel blends in diesel engine. Energy **44** (1), 955-963.

Muralidharan, K., Vasudevan, D., and Sheeba, K. N. (2011). Performance, emission and combustion characteristics of biodiesel fuelled variable compression ratio engine. Energy **36** (8), 5385-5393.

Murillo, S., Míguez, J. L., Porteiro, J., Granada, E., and Morán, J. C. (2007). Performance and exhaust emissions in the use of biodiesel in outboard diesel engines. Fuel **86** (12–13), 1765-1771.

Ng, J.-H., Ng, H. K., and Gan, S. (2011). Engine-out characterisation using speed–load mapping and reduced test cycle for a light-duty diesel engine fuelled with biodiesel blends. Fuel **90** (8), 2700-2709.

Ng, J.-H., Ng, H. K., and Gan, S. (2012). Characterisation of engine-out responses from a light-duty diesel engine fuelled with palm methyl ester (PME). Applied Energy **90** (1), 58-67.

Nabi, N. M., Najmul Hoque, S.M., and Shamim Akhter, Md. (2009). Karanja (Pongamia Pinnata) biodiesel production in Bangladesh, characterization of karanja biodiesel and its effect on diesel emissions. Fuel Processing Technology **90** (9), 1080-1086.

Oener, C. and Altun. (2009). Biodiesel production from inedible animal tallow and an experimental investigation of its use as alternative fuel in a direct injection diesel engine. Applied Energy **86** (10), 2114-2120.

Okona-Mensah, K., Battershill, J., Boobis, A., and Fielder, R. (2005). An approach to investigating the importance of high potency polycyclic aromatic hydrocarbons (PAHs) in the induction of lung cancer by air pollution. Food and Chemical Toxicology **43** (7), 1103-1116.

Onursal, B., and Gautam, S.P. 1997. Vehicular Air Pollution. The World Bank, Washington, DC.

Özener, O., Yüksek, L., Ergenç, A. T., and Özkan, M. (2012). Effects of soybean biodiesel on a DI diesel engine performance, emission and combustion characteristics. Fuel (0).

Özgünay, H., Çolak, S., Zengin, G., Sari, Ö., Sarikahya, H., and Yüceer, L. (2007). Performance and emission study of biodiesel from leather industry pre-fleshings. Waste Management **27** (12), 1897-1901.

Ozsezen, A. N., Canakci, M., Turkcan, A., and Sayin, C. (2009). Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. Fuel **88** (4), 629-636.

Parawira, W. (2010). Biodiesel production from *Jatropha curcas*: A review. Scientific Research and Essays 5.14: 1796-1808.

Performance Management and Delivery Unit (PEMANDU) (2010). Economic transformation programme: a roadmap for Malaysia. Chapter 9, Palm oil. PEMANDU, Prime Minister's Department, Malaysia.

Qi, D. H., Chen, H., Geng, L. M., and Bian, Y. Z. (2010a). Experimental studies on the combustion characteristics and performance of a direct injection engine fueled with biodiesel/diesel blends. Energy Conversion and Management **51** (12), 2985-2992.

Qi, D. H., Chen, H., Geng, L. M., Bian, Y. Z., and Ren, X. C. (2010b). Performance and combustion characteristics of biodiesel–diesel–methanol blend fuelled engine. Applied Energy **87** (5), 1679-1686.

Rajaraman, S., Yashwanth, G. K., T.Rajan, Kumaran, R. S., and P.Raghu. (2009). Experimental investigations of performance and emission characteristics of Moringa oil methyl ester and its diesel blends in a single cylinder direct injection diesel engine. Proceedings of the ASME 2009 International Mechanical Engineering Congress & Exposition, November 13-19, Lake Buena Vista, Florida, USA.

Ramadhas, Muraleedharan, C., and Jayaraj, S. (2005). Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil. Renewable Energy **30** (12), 1789-1800.

Rao, P. V. (2011). Experimental Investigations on the Influence of Properties of Jatropha Biodiesel on Performance, Combustion, and Emission Characteristics of a DI-CI Engine. World Academy of Science, Engineering and Technology **75**, 855-868.

Rashid, U., Anwar, F., Moser, B. R., & Knothe, G. (2008). Moringa oleifera oil: A possible source of biodiesel. Bioresource Technology, **99** (17), 8175-8179.

Ribeiro, N. M., Pinto, A. C., Quintella, C. M., da Rocha, G. O., Teixeira, L. S. G., Guarieiro, L. L. N., do Carmo Rangel, M., Veloso, M. C. C., Rezende, M. J. C., Serpa da Cruz, R., de Oliveira, A. M., Torres, E. A., and de Andrade, J. B. (2007). The Role of Additives for Diesel and Diesel Blended (Ethanol or Biodiesel) Fuels: A Review. Energy & Fuels **21** (4), 2433-2445.

Rodríguez, R. P., Perez, L. G., Alfonso, M., Duarte, M., Caro, R., Galle, J., Sierens, R., and Verhelst, S. (2011). Characterization of *Jatropha curcas* oils and their derived fatty acid ethyl esters obtained from two different plantations in Cuba. Biomass and Bioenergy **35** (9), 4092-4098.

Sahoo, P. K., Das, L.M., Babu, M.K.G., and Naik, S.N. (2007). Biodiesel development from high acid value polanga seed oil and performance evaluation in a CI engine. Fuel **86** (3), 448-454.

Sahoo, P. K., Das, L.M., Babu, M.K.G., Arora, P., Singh, V.P., Kumar, N.R., Varyani, T.S. (2009). Comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel as fuel in a tractor engine. Fuel, 88(9), 1698-1707.

Saleh, H. E. (2009). Experimental study on diesel engine nitrogen oxide reduction running with jojoba methyl ester by exhaust gas recirculation. Fuel **88** (8), 1357-1364.

Sanford, S., White, J., Shah, P., Wee, C., Valverde, M., and Meier, G. (2011). Feedstock and Biodiesel Characteristics. Retrieved 23th February, 2013, from http://wwwregfuelcom/pdfs/Feedstock%20and%20Biodiesel%20Characteristics%20Reportpdf.

Saravanan, N., Nagarajan, G., and Puhan, S. (2010). Experimental investigation on a DI diesel engine fuelled with Madhuca Indica ester and diesel blend. Biomass and Bioenergy **34** (6), 838-843.

Saravanan, S., Nagarajan, G., and Narayana Rao, G. L. (2009). Feasibility analysis of crude rice bran oil methyl ester blend as a stationary and automotive diesel engine fuel. Energy for Sustainable Development **13** (1), 52-55.

Selvam, D. J. P., and Vadivel, K. (2012). Performance and Emission Analysis of DI Diesel Engine Fuelled with Methyl Esters of Beef Tallow and Diesel Blends. Procedia Engineering **38** (0), 342-358.

Shahabuddin M, Kalam M.A, Masjuki, H. H., Bhuiya, M. M. K., and Mofijur, M. (2012). An experimental investigation into biodiesel stability by means of oxidation and property determination. Energy **44** (1), 616-622.

Shahabuddin, M., Liaquat, A. M., Masjuki, H. H., Kalam, M. A., and Mofijur, M. (2013). Ignition delay, combustion and emission characteristics of diesel engine fueled with biodiesel. Renewable and Sustainable Energy Reviews **21** (0), 623-632.

Shahabuddin, M., Masjuki, H. H., Kalam, M. A., Mofijur, M., Hazrat, M. A., and Liaquat, A. M. (2012). Effect of Additive on Performance of C.I. Engine Fuelled with Bio Diesel. Energy Procedia **14** (0), 1624-1629.

Sharma, D., Soni, S. L., and Mathur, J. (2009). Emission Reduction in a Direct Injection Diesel Engine Fueled by Neem-Diesel Blend. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects **31** (6), 500-508.

Silitonga, A. S., Atabani, A. E., Mahlia, T. M. I., Masjuki, H. H., Badruddin, I. A., and Mekhilef, S. (2011). A review on prospect of *Jatropha curcas* for biodiesel in Indonesia. Renewable and Sustainable Energy Reviews **15** (8), 3733-3756.

Singh, S. P. and Singh, D. (2010). Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: A review. Renewable and Sustainable Energy Reviews **14** (1), 200-216.

Srivastava, A. and Prasad, R. (2000). Triglycerides-based diesel fuels. Renewable and Sustainable Energy Reviews **4** (2), 111-133.

Tan, P.-q., Hu, Z.-y., Lou, D.-m., and Li, Z.-j. (2012). Exhaust emissions from a light-duty diesel engine with Jatropha biodiesel fuel. Energy **39** (1), 356-362.

Tsolakis, A., Megaritis, A., Wyszynski, M. L., and Theinnoi, K. (2007). Engine performance and emissions of a diesel engine operating on diesel-RME (rapeseed methyl ester) blends with EGR (exhaust gas recirculation). Energy **32** (11), 2072-2080.

Ulusoy, Y., Arslan, R., and Kaplan, C. (2009). Emission Characteristics of Sunflower Oil Methyl Ester. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects **31** (11), 906-910.

Usta, N. (2005a). An experimental study on performance and exhaust emissions of a diesel engine fuelled with tobacco seed oil methyl ester. Energy Conversion and Management **46** (15-16), 2373-2386.

Usta, N. (2005b). Use of tobacco seed oil methyl ester in a turbocharged indirect injection diesel engine. Biomass and Bioenergy **28** (1), 77-86.

Wang, X., Ge, Y., Yu, L., and Feng, X. (2013). Comparison of combustion characteristics and brake thermal efficiency of a heavy-duty diesel engine fueled with diesel and biodiesel at high altitude. Fuel **107** (0), 852-858.

Xue, J., Grift, T. E., and Hansen, A. C. (2011). Effect of biodiesel on engine performances and emissions. Renewable and Sustainable Energy Reviews **15** (2), 1098-1116.

Zhang, Q., and Zhu Y. (2010). Measurements of ultrafine particles and other vehicular pollutants inside school buses in South Texas. Atmospheric Environment **44** (2), 253-261.

Zhihao, M., Xiaoyu, Z., Junfa, D., Xin, W., Bin, X., and Jian, W. (2011). Study on Emissions of a DI Diesel Engine Fuelled with Pistacia Chinensis Bunge Seed Biodiesel-Diesel Blends. Procedia Environmental Sciences **11** (C), 1078-1083.

APPENDIX A

PUBLICATIONS

Journal Articles:

Mofijur, M., Atabani, A. E., Masjuki, H. H., Kalam, M. A., Masum, B. M. (2013). A study on the effects of promising edible and non-edible biodiesel feedstocks on engine performance and emissions production: A comparative evaluation. Renewable and Sustainable Energy Reviews **23** (0), 391-404. **(ISI Q1)**

Mofijur, M., Masjuki, H. H., Kalam, M. A., Atabani, A. E. (2013). Evaluation of biodiesel blending, engine performance and emissions characteristics of *Jatropha curcas* methyl ester: Malaysian perspective. Energy **55** (0), 879-887. **(ISI Q1)**

Mofijur, M., Masjuki, H. H., Kalam, M. A., Atabani A.E., Liaquat A.M., S.M. Ashrafur (2013). Performance and emission analysis of Jatropha curcas and Moringa oleifera methyl ester fuel blends in a multi-cylinder diesel engine. Journal of Cleaner Production. In press corrected proof, available online 5 September 2013 **(ISI Q1).**

International Conference:

M. Mofijur, H.H Masjuki, M.A. Kalam, M. Shahabuddin. Comparative performance analysis of a compression ignition engine fuelled with biodiesel blends. “The Energy & Materials Research Conference (EMR 2012)”. 20-22 June, 2012, Malaga, Spain.

APPENDIX B

FUEL PROPERTIES OF BIODIESEL BLENDS

Fuel Properties of Palm Biodiesel Blends:

SL	Properties	PB10	PB20	PB30	PB40	PB50	PB60	PB70	PB80	PB90	B100
01	Dynamic viscosity at 40°C (mPa.s)	2.84	2.92	3.03	3.15	3.27	3.39	3.54	3.67	3.84	3.97
02	Kinematic viscosity at 40°C (mm^2/s)	3.39	3.47	3.60	3.73	3.85	3.99	4.15	4.29	4.49	4.63
03	Kinematic viscosity at 100°C (mm^2/s)	1.33	1.37	1.41	1.46	1.50	1.55	1.60	1.65	1.71	1.78
04	Density (kg/m^3)	837.9	840.1	842.4	844.5	848.1	849.2	851.8	854.4	856.8	858.9
05	Viscosity index	140.3	149.8	159.9	167.3	172.7	177.5	185.6	188.0	188.7	195.8
06	Cold Filter Plugging Point (°C)	6	4	4	3	3	3	6	9	11	11
07	Cloud Point (°C)	8	7	7	7	6	5	7	8	11	10
08	Pour Point (°C)	-1	-1	-1	2	2	5	8	8	8	11
09	Flash point (°C)	77.5	78.5	83.5	85.5		93.5	99.7	112.5	143.2	182.5
10	Calorific value (MJ/Kg)	44.651	43.995	43.325	42.979	42.040	41.726	41.179	40.757	40.183	40.907

Fuel Properties of Jatropha Biodiesel Blends:

SL	Properties	JB10	JB20	JB30	JB40	JB50	JB60	JB70	JB80	JB90	JB100
01	Dynamic viscosity at 40°C (mPa.s)	2.84	3.03	3.12	3.25	3.39	3.51	3.67	3.79	3.95	4.09
02	Kinematic viscosity at 40°C (mm^2/s)	3.42	3.63	3,72	3.86	4.01	4.13	4.3	4.42	4.58	4.73
03	Kinematic viscosity at 100°C (mm^2/s)	1.34	1.42	1.45	1.51	1.56	1.60	1.68	1.71	1.76	1.82
04	Density (kg/m^3)	831	834.9	839	842.2	846	849.7	854	857.6	862	865.7
05	Viscosity index	143	159	167	175.7	181	187	194.7	202.6	208	214.7
06	Cold Filter Plugging Point (°C)	6	6	7	8	9	12	15	15	17	18
07	Cloud Point (°C)	6	6	6	6	5	5	4	3	3	3
08	Pour Point (°C)	0	0	0	0	1	2	2	3	3	3
09	Flash point (°C)	80.3	84	86.5	90	94	112	128	145	160.5	184.5
10	Calorific value (MJ/Kg)	44.728	44.191	43.549	42.889	42.22	41.543	41.225	40.573	40.278	39.827

Fuel Properties of Moringa Biodiesel Blends:

SL	Properties	MB10	MB20	MB30	MB40	MB50	MB60	MB70	MB80	MB90	MB100
01	Dynamic viscosity at 40°C (mPa.s)	2.94	3,.06	3.19	3.35	3.50	3.66	3.81	3.50	4.19	4.34
02	Kinematic viscosity at 40°C (mm^2/s)	3.55	3,.67	3.82	3.99	4.15	4.32	4.48	4.68	4.89	5.05
03	Kinematic viscosity at 100°C (mm^2/s)	1.36	1.39	1.48	1.52	1.55	1.64	1.66	1.75	1.82	1.84
04	Density (kg/m^3)	830.6	833.6	836.4	840.1	843.4	846.7	849.8	853.5	857.1	859.6
05	Viscosity index	101.1	111.6	121.1	131	140	150.1	157.6	174.7	181.4	184.6
06	Cold Filter Plugging Point (°C)	6	6	7	8	9	12	15	15	17	18
07	Cloud Point (°C)	7	8	9	12	13	14	15	17	18	19
08	Pour Point (°C)	3	6	9	10	12	14	17	16	19	19
09	Flash point (°C)	79.5	82.5	90	94.5	98	105.5	108.5	114.5	131	180.5
10	Calorific value (MJ/Kg)	44.749	43.984	43.869	43.270	42.643	41.842	41.529	40.919	40.389	40.052

APPENDIX C

Summary of measurements uncertainty

Measurements	Accuracy	Relative Uncertainty
Load	± 1 N	± 0.2
Speed	± 10 rpm	± 0.1
BP	± 0.07 kW	±0.243
BSFC	± 5 g/kWh	±0.013
CO	±0.001 %vol	±0.003
NO	±1 ppm	±0.005
HC	±1 ppm	±0.090
CO_2	± 0.01%vol	±0.001