PERFORMANCE CHARACTERISTICS OF A DIESEL ENGINE RUN ON BIODIESEL FUEL AND BLENDS

BY

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DECLARATION

I hereby declare that this submission is my own work towards the Doctor of Philosophy in Mechanical Engineering degree and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgment has been made in the text.

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ACRONYMS

BSEC	brake specific energy consumption
BSFC	brake specific fuel consumption
PKOME	palm kernel oil methyl ester
COME	coconut oil methyl ester

JCME	Jatropha curcas methyl ester (also Jatropha oil biodiesel)
CN	Cetane Number
Petrodiesel	Petroleum diesel
FAME	Fatty acid methyl ester
C.I	Compression Ignition
CIDI	Compression Ignition Direct Injection
NOx	Oxides of Nitrogen
CO	Carbon Monoxide
THC	Total Hydrogen Carbon
HC	Hydrocarbon
EGR	Exhaust Gas Recirculation
POME	Palm oil methyl ester
JME	Jatropha methyl ester
SVO	Straight Vegetable Oil
AV	Acid value
B100	100% Biodiesel
B50	50% Biodiesel and 50% petroleum diesel
B5	5% Biodiesel and 95% petroleum diesel
B10	10% Biodiesel and 90% petroleum diesel
FFA	Free fatty acid
BTDC	Before Top Dead Centre
CAD	Crank angle degrees
TDC	Top dead centre
BDC	Bottom dead centre
BTE	Brake Thermal Efficiency
ASTM	American Society for Testing and Materials
ASTM D6751	ASTM biodiesel specification standard
CFPP	Cold filter plugging point
EN	European standards
EN 14214	EN biodiesel specification standard
FP	Flash point

CP	cloud point
OEM	Original equipment manufacturers
CI-IDI	Compression Ignition, Indirect Injection

ABSTRACT

Literature is replete with much research on the performance of biodiesel blends with petroleum in a diesel engine. Much of the researches did not consider the effect of biodiesel-biodiesel blends and injection system modifications on engine performance. The focus of this work is to examine the performance of biodiesels of Ghanaian origin namely Palm Kernel biodiesel (PKOME), Jatropha biodiesel (JCME), Coconut biodiesel (COME) and their biodiesel-biodiesel blends in a VW, four-cylinder, fourstroke, indirect injection engine which is turbocharged and air cooled. The combined effect of injection timing and pressure on engine performance are also investigated and their results compared with petroleum diesel results. Torque, brake power, brake specific fuel consumptions and brake thermal efficiencies were recorded for each fuel tested at varying engine speeds on an eddy current dynamometer. Petroleum diesel recorded at least 5% higher brake power and torque than biodiesel at all engine speeds. Brake specific fuel consumption of petroleum diesel was found to be 5% lower than biodiesel at all engine speeds. At initial engine speeds, biodiesel recorded higher thermal efficiencies of about 39% compared with petroleum diesel of 38% at 1800 rpm. Engine modifications were carried out for each fuel used except petroleum diesel. The input factors for the modification include injection timing only, injection pressure only and their combined effects on brake specific energy consumption and exhaust emissions particularly Carbon monoxide, Hydrocarbons and oxides of Nitrogen were investigated. Injection timing was varied at six (6) levels including advance of 9 ^{0}, 6 ^{0}, 3 ^{0} settings and retardation settings of 6 ^{0} and 3 ^{0} while the engine default timing settings was kept at 0 ^{0}. Injection pressure in increments of

25 bars in the range of 150 bars to 250 bars was used. Generally, higher fuel injection pressures produced lower fuel consumption. For PKOME and COME, fuel injection pressure of 250 bars and an advance timing of 3^0 were found to have the lowest fuel economy and least tail pipe emissions. The optimal values for JCME were found to be at a pressure of injection of 200 bar and an advance timing of 3^0. PKOME and COME were blended in proportions of 100%, 75%, 50% and 25% by volume to determine the best blend for improved physiochemical properties for enhanced engine performance. JCME was also blended with COME in the same proportions by volume. In terms of exhaust emissions and fuel consumption, the optimum values were obtained with 75% COME and 25% PKOME by volume. Brake specific energy consumption (BSEC) of 15.4 MJ/kWh and emission values of CO = 0.39 Vol. %, HC = 45 ppm and NOx = 146 ppm was obtained.

The optimum blend of JCME and COME was in the proportion of 75% JCME and 25% COME by volume. This also yielded BSEC of 13 MJ/kW-h, CO of 0.24 Vol. %, HC of 65 ppm and NOx emissions of 256 ppm, respectively. Petroleum diesel engine runs recorded BSEC of 11.8 MJ/kW-h, CO of 0.43 Vol. %, HC of 103 ppm and NOx of 140 ppm. Both BSEC and emissions were improved when biodiesels were blended with each other. Emissions of petroleum diesel such as Carbon monoxide and Hydrocarbons were 80 % and 50 % respectively higher than that of the best biodieselbiodiesel blend by volume. Engine runs of PKOME-JCME blends were not conducted because JCME and COME feedstocks have very similar properties.

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CHAPTER ONE

1. INTRODUCTION

1.1. Background

Increasing industrialization has led to an upward surge in demand for petroleum products (Agarwal, 2007). Demand for petroleum products by the transportation and industrial sector will account for 92% of global liquid fuels demand in 2040 as economies move from a subsistence to an industrial or service base economy (Ieo, 2014). Economic development causes growth in the industrial sector which entails transport of goods for manufacture and manufactured goods after manufacture. By 2030 about half of the increase in global energy demand will be for power generation. The demand for petroleum is predicted to surge speedily in the transport sector over the next 25 year (Ieo, 2007). Up to 80% prime energy expended in the world is fossil fuels of which 58% is used for transport (Escobar, Lora, Venturini, Yáñez, Castillo & Almazan, 2009). It has been estimated that oil production will show a downward trend to become just 35% of today's production by the year 2075 (Aliyu, Shitanda, Walker, Agnew, Masheiti & Atan, 2011). From 2000 through 2008, petrodiesel consumption increased by 23%, other petroleum products consumption grew by 7% (Ieo, 2007). Figure 1.1 below gives the general trend in the rise of world diesel consumption compared with other fuels.

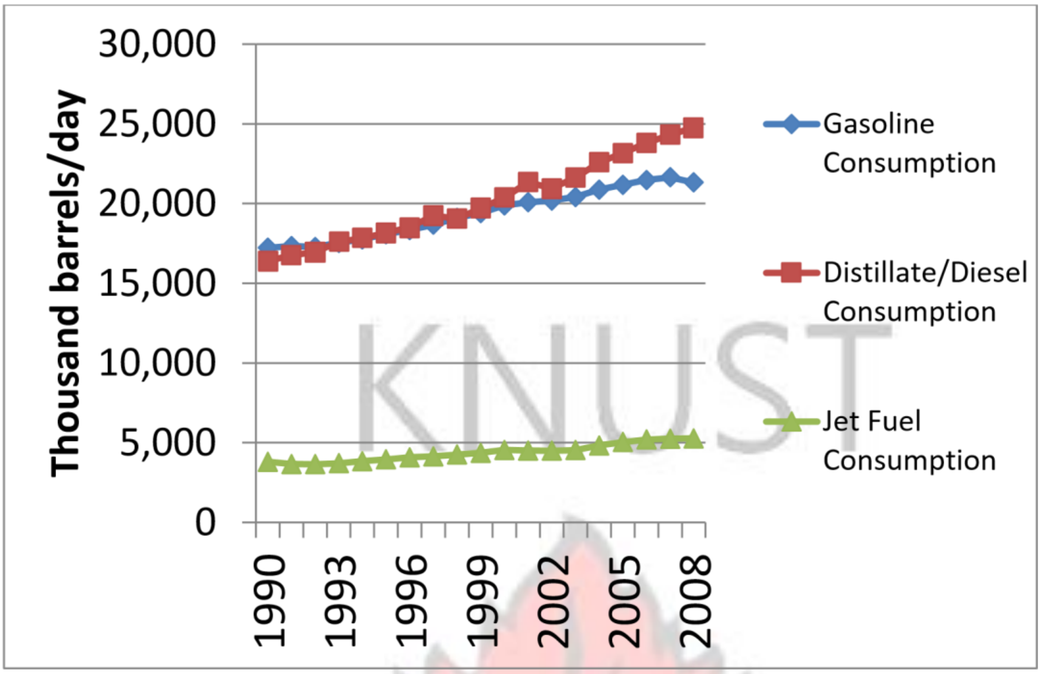


Figure 1.1 Worldwide consumption of Diesel, Gasoline and Jet Fuel (NPA, 2014)

Similarly, in Ghana the demand for diesel and gasoline are expected to grow at rates of 10 percent and 9 percent per annum, respectively (Essandoh-Yeddu, 2006). Indeed, diesel is the most demanded and consumed petroleum fuel in Ghana (Figure 1.2). The National Petroleum Authourity (NPA) has reported that petrodiesel fuel consumption in Ghana 41% of the petroleum produces consumption. The annual rate of consumption of petrodiesel growth in Ghana is a rate of 5% annually (NPA, 2014).

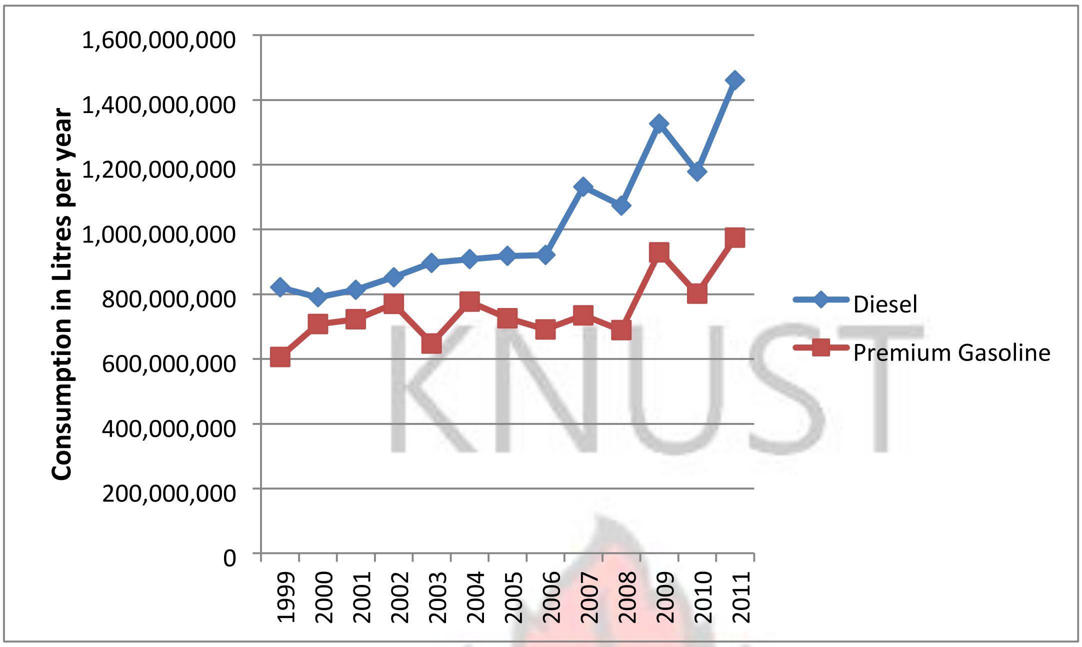


Figure 1.2 Diesel and Gasoline consumption trend in Ghana (NPA)

This is due to the fact that petrol has fewer applications (more than 98% as vehicle fuel), while diesel has a number of applications (Kavalov & Peteves, 2004). Though Road transportation is a major part, it is not the only petrodiesel consuming sector. Diesel fuel is used also in industries such as the mining industries and homes to power generators. For the reasons aforementioned, this research is focussed on performance characteristics of a diesel engine run on biodiesel fuel and its blends.

Biodiesel also referred to as Methyl Ester, is environmentally friendly consisting of fatty acids (see Appendix F for production path). It is produced from triglycerides by the method of transesterification. It is an alternative fuel that may help to reduce the overdependence of the world on petroleum diesel which also has very substantial benefits to the environment. The reasons for these environmental benefits are that it is an oxygenate, sulphur free, and a biodegradable fuel. It is well known and mostly reported that biodiesel has less tail pipe emissions. Especially total hydrocarbons, carbon monoxide and soot emissions are less (Wan Ghazali, Mamat, Masjuki & Najafi, 2015). In its press release the Agency of research on cancer, an arm of WHO, classified petrodiesel tail pipe emissions as capable of causing lung cancer. Among its recommendations is that alternatives to diesel should be considered especially in Research and Development (R&D).

Ghana government has set a Strategic National Energy Plan (SNEP) 2006-2020 to make B5 (5% biodiesel and 95% petrodiesel) and B10 (10% biodiesel and 90% petrodiesel) mandatory for sale at all service stations by the year 2020 (SNEP, P.57). In the year 2020, Ghana is expected to consume 4.5 million tonnes of petroleum products. More than 450, 000 tonnes of vegetable oil will have to be met by year 2020 in order to meet this target (Kuwornoo & Ahiekpor, 2010). There are however no indications of this coming to fruition as no blending centres are being set up and no feedstock is being considered presently.

Most experts have suggested Palm Oil as the best feedstock for Ghana's biodiesel as opposed to Jatropha as fuel because of production trend (Figure 1.3). The economic viability of Jatropha as fuel crop has not been proven well enough. Though drought resistant, yields are not better than other crops (Iddrisu & Bhattacharyya, 2015). However, according to the Ministry of Agriculture (MoFA), Ghana currently has an unmet demand of 35000 tons of Palm Oil per year. (Afrane, 2012) reports that the solution to utilisation of biodiesel in Ghana will be to supplement Palm Oil with other biodiesel feed stocks. This is why as part of this research, performance of Palm Kernel Oil Methyl Ester (PKOME), Coconut Oil Methyl Ester (COME) and Jatropha Oil Methyl Ester (JCOME) blends in a diesel engine will be experimented and analysed.

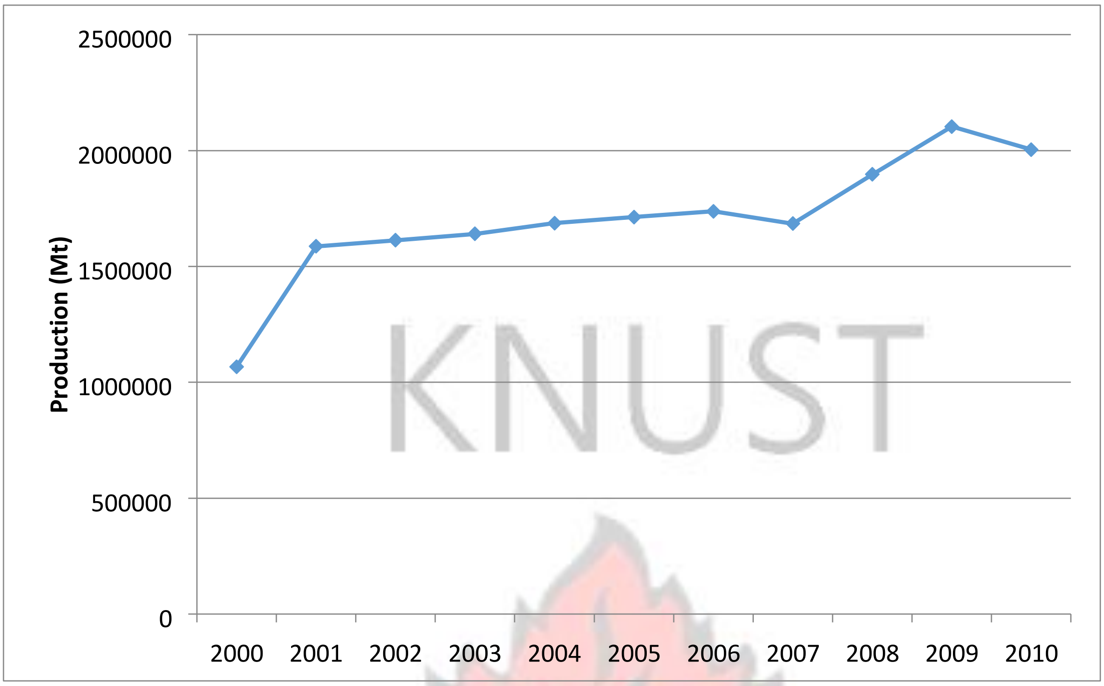


Figure 1.3 Ghana's increasing Palm oil production trend (SRID, 2011)

1.2. Justification for biodiesel research

Over 100 feedstocks have since 2015, been discovered for making biodiesel. The choice of which feedstock is adapted by a country depends on availability, cost and whether it is edible or not. Argentina prefers to use soybean oil. But China, prefers palm oil because there is a high demand for soybean for preparation of Chinese food (Beckman & Yang, 2009). Palm oil is preferred in Asian countries since they have surplus in production but oil from rapeseed is mostly used in Europe. Some countries such as Ghana are struggling to choose their preferred feedstock since there is not enough of any of the oils whether edible or not.

In spite of numerous advances in biodiesel production technology no major Original Equipment Manufacturer (OEM) gives warranty for B100 use. The stance of the OEM is because not every biodiesel is the same. Even physiochemical properties of biodiesel from the same feedstock may differ depending on the species, mode of preparation, water content, type or catalyst concentration, alcohol molar and even time used for reaction. The quality of feedstock is not guaranteed. This is why to shield consumers from buying low standard fuel out of ignorance, the OEMs have stated formally that the biodiesel must meet ASTM D-6751 (American Society for Testing and Materials) or/and EN14214 (European Committee for Standardization).

Much of engine research is therefore required for B100. It has been reported that only B20 meet the European Union requirements of for biodiesel performance (Mofijur, Masjuki, Kalam & Atabani, 2013). Hence, only up to B20 have been used to assess engine performance. This is evident in Table 1.1.

Table 1.1 Work done on the three feedstocks so far

Feedstock	Proportion	Engine Tested	Methodology	References
PKOME	B100	no engine tests conducted	Biodiesel production	[1,2,3,4,5,6,7,8,9]
COME	B20	4-cylinder diesel engine	Emissions test, BSFC	[10,11,12,13]
	B100	No engine tests	Properties	[14,15,16,17]
JCME	B20 and B50	Engine test	Engine performance	[18, 19,20,21,22]
	B100	Engine tests	Emissions	[23]

[1](Stamenković, Veličković & Veljković, 2011)
[2](Llamas, García-Martínez, Al-Lal, Canoira & Lapuerta, 2012)
[3](Alamu, Waheed & Jekayinfa, 2007)
[4](Alamu, Akintola, Enweremadu & Adeleke, 2008a)
[5](Alamu, Waheed & Jekayinfa, 2008b)
[6](Limmanee, Naree, Bunyakiat & Ngamcharussrivichai, 2013)
[7](Vasiliou, Bouriazos, Tsichla & Papadogianakis, 2014)
[8](Benjapornkulaphong, Ngamcharussrivichai & Bunyakiat, 2009)
[9](Jitputti, Kitiyanan, Rangsunvigit, Bunyakiat, Attanatho & Jenvanitpanjakul, 2006)
[10](Rizwanul Fattah, Masjuki, Kalam, Wakil, Rashedul & Abedin, 2014)
[11](How, Masjuki, Kalam & Teoh, 2014)
[12](Liaquat, Masjuki, Kalam, Fattah, Hazrat, Varman, Mofijur & Shahabuddin, 2013)
[13](Habibullah, Masjuki, Kalam, Rizwanul Fattah, Ashraful & Mobarak, 2014)
[14](Atabani, Silitonga, Badruddin, Mahlia, Masjuki & Mekhilef, 2012)
[15](Zanuttini, Pisarello & Querini, 2014) [16](Tasić, Stamenković & Veljković, 2014)
[17](Atabani, Mahlia, Masjuki, Badruddin, Yussof, Chong & Lee, 2013)
[18]Agarwal, 2007 [18](Tupufia, Jeon, Marquis, Adesina & Rogers, 2013)
[19](Ong, Masjuki, Mahlia, Silitonga, Chong & Yusaf, 2014)
[20](Mofijur *et al.*, 2013)
[21](El-Kasaby & Nemit-Allah, 2013)
[22](Rahman, Masjuki, Kalam, Abedin, Sanjid & Imtenan, 2014)
[23](Tan, Hu, Lou & Li, 2012)

In the case of PKOME no engine runs have been conducted let alone engine optimisation. Engine runs have been conducted for COME but only up to B20 and no further research of B100 have been conducted. This is the same for JCME where engine runs have been up to B50. While much focus has been on biodiesel-petrodiesel blends, engine runs for biodiesel-biodiesel blends are yet to be conducted.

Appropriate feedstock selection and production technology is therefore vital for biodiesel production (Issariyakul & Dalai, 2014). Some gaps exist in biodiesel production from feedstock like coconut oil and palm kernel. Some such as Żarska, Bartoszek and Dzida (2014:) have studied high physiochemical properties of coconut oil focusing on temperature and pressure neglecting physiochemical properties. Others studied in situ (Trans) esterification of coconut oil using mixtures of methanol and tetrahydrofuran but did not consider yield or catalyst concentration (Khang, Razon, Madrazo & Tan, 2014). Concentration of catalyst and ratio of methanol and oil has been investigated for the production of coconut oil but their combined effect on yield has been neglected and base catalysed (Trans) esterification has not been considered (Nakpong & Wootthikanokkhan, 2010). Ethanolysis of coconut oil to produce biodiesel has been done but the methanol, catalyst concentration and their effect biodiesel from coconut on yield has not been specified (Kumar, Kumar, Poonam & Singh, 2010).

Work done on biodiesel (B100) have not considered certain vital details. One study is recorded to have been carried out on production of PKOME with KOH (base catalyst) but production with NaOH as base catalyst is yet to be considered (Alamu *et al.*, 2008b, 2007).) Pullen and Saeed (2014:) stated in their recommendation that influence of type of alcohol in biodiesel production and use is tentative. There is therefore a need for further investigation here. Characterisation of PKOME in the literature have not included cetane numbers and calorific values and neither are the species from which the oils were obtained mentioned. There are many species of palm oil from which palm kernel oil can be produced. These species include *Elaeis oleifera* commonly called

American oil palm, *Elaeis guineensis* also called the African oil palm and *Butia capitata* also called Jelly palm usually grown in Argentina, Brazil and Uruguay.

It has been found and reported that the biodiesel yield is greatly influenced by ratio of methanol and oil and concentration of catalyst (Rashid, Uemura, Kusakabe, Osman & Abdullah, 2014). The main stage of biodiesel production is the transesterification reaction. The ratio of the alcohol (methanol or ethanol) to oil strongly influences the yield. The ideal ratio to use hinges on the feedstock source. This reaction is facilitated by a catalyst such as KOH or NaOH. (Aransiola, Ojumu, Oyekola, Madzimbamuto & Ikhu-Omoregbe, 2014).

This research investigates the effect of process parameters including methanol to oil ratio, NaOH base catalyst concentration on coconut, palm kernel and Jatropha biodiesel yield. The influence of sulphuric acid (H_2SO_4) on viscosity has also been investigated for PKOME, COME and JCME. Running biodiesel successfully also depends on the biodiesel production process (Atadashi, Aroua & Aziz, 2010).

Therefore, when diesel is completely replaced by biodiesel it is apparent that engine modifications are required. This is to avoid degradation in engine performance, pollution and engine durability issues. NOx is known to increase when biodiesel is used because excess oxygen in biodiesel can lead to high temperatures leading to NOx formation. Thermal efficiency, brake torque and brake power will all decrease significantly with biodiesel usage owing to lower calorific value of biodiesel. For the same reason BSFC and BSEC will all increase making it more expensive to use biodiesels. Injection features have an enormous effect on engine power especially if no modifications has been applied to the engine. It is important to in the future investigate the precise connection between injection pressure and timing to find the optimal combination when biodiesel is in use (Ong *et al.*, 2014). Biodiesel fuel consumption is influenced by the type of engine and performance characteristics such as engine speed, air to fuel ratio, load and timing and pressure of injection. Further performance studies conditions are recommended in order to obtain best match for biodiesel performance (Singh & Singh, 2010). It is usually recommended that engine redesign or adjustment be considered for B100. Injection system parameter adjustment have been suggested to be at the forefront of this adjustment (Xue, Grift & Hansen, 2011). The primary objective of work from now must be research on B100 run engines and not biodiesel-petrodiesel blends (Sharma, Singh & Upadhyay, 2008).

This work therefore also examines the effect of timing and pressure of injection and their combined effect on engine performance of coconut, palm kernel and Jatropha oil biodiesel. The investigation will also determine the optimization parameters for each feedstock.

Unfortunately the use of biodiesel is hindered by two major social factors. First depending on feedstock, it may be edible and hence its use as biodiesel competes with its use as food. Secondly, the feedstock might not be readily abundant. For instance, the most readily available oil source for the making methyl esters in Ghana is Palm oil. However, Ghana is a net importer of palm oil (Afrane, 2012). But it will be more realistic if it is blended with biodiesels from other feedstock such as palm kernel oil, coconut oil or Jatropha oil which are also readily available but not preferred for consumption compared to palm oil.

When Rudolph Diesel invented the diesel engine he used oil from peanut which is a type of raw vegetable oil, as fuel (Hossain & Davies, 2012). The diesel engine developed was successfully run on oils from vegetable and required no modification. Physiochemical vegetable oil properties are similar to petrodiesel oil and therefore are similar fuels. However, several issues have been reported when vegetable oils are run on petrodiesel engines. This is as a result of the lower cetane number and higher viscosities of vegetable oils giving rise to a number of difficulties in petrodiesel engines such as engine chocking, injector coking, gum formation, choked filters, and deposits in the engine combustion cylinder under long term use have been reported (Wang, Al-Shemmeri, Eames, Mcmullan, Hewitt, Huang & Rezvani, 2006). What is unknown in literature is whether blending biodiesels of different feed stocks could improve the physiochemical properties of the biodiesel. If it is favourable to replace petro-diesel, then how favourable is it? Much research has been done on biodiesel blends with petroleum diesel but to the best of my knowledge little is known of biodiesel/biodiesel blends. This study focuses on analysis of blends of palm kernel oil biodiesel, coconut oil and Jatropha biodiesel to decide optimum physio-chemical properties and performance in the diesel engine compared to petroleum diesel.

Finally, as part of this work, effect of biodiesel-biodiesel blends (PKOME, COME and JCME) on physiochemical properties, engine emissions and fuel consumption are studied and optimized blends suggested.

1.3. Problem Statement

Ghana has a policy to implement B10 by 2020 but no Research and Development is taking place to facilitate this. There is not enough adequate data on which conclusive decisions concerning material compatibility and durability of engine fuel systems can be based. The engine characteristics needed to be adapted for optimum engine performance are largely unknown. The effect of blending feedstock is also yet to be investigated. Fossil fuels are being exhausted. These fossil fuels contribute a lot to greenhouse gas emissions. There are many negative effects of fossil fuel usage such as greenhouse effects leading to rise in sea level, climate change and receding of glaciers (Gullison, Frumhoff, Canadell, Field, Nepstad, Hayhoe, Avissar, Curran, Friedlingstein, Jones & Nobre, 2007). Lessening of engine tail pipe emissions is an important factor in engine research. Since biodiesel is a biodegradable, it reduces particulate, hydrocarbon, and carbon monoxide emissions from petrodiesel tailpipe emissions. Biodiesel has very favourable effects environmentally, for example its biodegradability, reduction in greenhouse emissions and acid rain. Biodiesel for instance exhibits a 41% reduction in greenhouse emissions compared to petrodiesel (Hill, Nelson, Tilman, Polasky & Tiffany, 2006). Conventional biodiesel constitutes 60 % less CO, 80% less CO_2, 85% less SO_2 and 55% less THC (Knothe & Steidley, 2005; Krahl, Munack, Schroder, Stein, Herbst, Kaufmann & Bunger, 2005). Because biodiesels have different chemical composition compared with petroleum diesel, some modifications are necessary for its engine use. Knowing the exact modifications to apply such as in injection timing and pressure will increase performance of biodiesel engines and ease its use. Developing countries are struggling to adapt a single feedstock for biodiesel use because of issues of availability and competition with food.

In such cases, blending biodiesel of different feedstocks could be appropriate to augment feedstock supplies. The effect of different feedstocks on each other in terms of physiochemical properties and engine performance will be useful in determining whether blending different biodiesel feedstocks should be recommended. Biodiesel quality is one of concern to OEMs because it affects its use as fuel. If the quality is compromised some vehicle components could be damaged long before its determined lifespan. To further boost biodiesel supply and its use, it will be prudent to investigate how its yield and quality can be increased in terms of production.

1.4. Aim

As biodiesel research continues at a very fast rate, the growth of more feedstocks and developments in biodiesel making processes provide the solution to the transformation of biodiesel into a viable energy resource. This work aim to promote the transition to to biodiesel use and to reduce the overdependence on petrodiesel considering the looming dangers of climate change and the depletion of fossil fuel reserves.

1.5. Objectives

As has been stated in the Justification in spite of the many works done on biodiesel there are gaps in literature. For example, focus has always been on biodiesel and its blends with petrodiesel. This study is grounded on using biodiesel of different feedstock to improve properties and performance instead of using petroleum diesel to improve biodiesel performance. Engine optimisation has largely been neglected and earlier studies suggest that engine parameters have been considered using the method of changing a parameter at a time. Burning processes in petrodiesel engines are mostly affected by combined effects of a number of parameters instead of just one parameter. Compression ratio, piston size, EGR, injection pressure and injection timing may have more pronounced combined effects than their individual effects. Therefore, use of Design of Experiments (DoE) tools such as JMP and Design Expert are to aide explore the combined effect of these parameters (Pandian, Sivapirakasam & Udayakumar, 2011). Another purpose of the thesis was to examine the impact of injection timing and pressure on fuel economy and exhaust tail pipe emissions of a petrodiesel engine fuelled by PKOME, COME and JCME using full factor factorial design. The following specific objectives were considered in this work to fill the gaps in literature:

1. To determine performance characteristics of blends of PKOME-COME and JCMECOME based on BSEC and Carbon monoxide, Hydrocarbon and Oxides of nitrogen emissions

2. To determine optimal parameters of injection timing and pressure and their combined effect on COME, PKOME and JCME fuelled diesel engine characteristics

3. To determine optimal parameters of catalyst concentration and molar ratio of methanol and oil for high yield production of PKOME, COME and JCME.

1.6. Scope of Work

The results of this work can be applied to road vehicles, stationary diesel engines such as diesel generators, corn mills and agricultural machinery that use petroleum diesel fuel. Biodiesel from only three feedstocks have been considered namely oils from Palm Kernel, Jatropha and coconut and their biodiesel-biodiesel blends. Their engine performance characteristics were measured as emissions and engine economy while the engine optimisation was realized by injection timing and pressure variations.

1.7. Significance of Study

Petrodiesel fuels are influential for livelihoods in an industrialised or developing country. Their applications range from heavy duty machinery, transportation, locomotives, generators, farm implements, earth-moving machinery and mining equipment. It has become necessary to develop a viable alternative fuel to petrodiesel due to depleting fuel reserves and for the sake of protecting the environment. It is also to reduce the cancerous effect of diesel tailpipe emissions on humans. Substituting a minimum fraction of total petrodiesel consumption with alternative will have enormous economic and environmental advantages for a country. This research is significant to the Country in the sense that it will help in Ghana's preparedness to adopt biodiesel in future. At the end of the research optimized parameters in terms of pressures and timings of injection for the operation of B100 (PKOME and COME) in a diesel engine would be obtained. Optimized parameters for biodiesel production form maximum yield and best properties has also been prescribed. With the adoption of palm and palm kernel oil as biodiesel in Ghana, employment in the rural sectors will increase. In Ghana, most people involved in the production of palm and palm kernel oil are women from the rural area. If there is significant breakthrough in biodiesel usage in engines, it will empower these women financially and influence many families as well.

CHAPTER TWO

2. LITERATURE REVIEW

Petroleum diesel is a fuel considered for compression ignition engines as opposed to petrol considered for spark ignition engines. Whether a fuel can be considered as an alternative or not depends on the physiochemical properties of the fuel. Petroleum diesel has properties similar to biodiesel just as petrol has properties similar to bioethanol or liquefied petroleum gas. This chapter reviews issues on petroleum fuel properties and compares with biodiesel. A review of other works on engine performance using biodiesel and petroleum diesel has also been considered.

2.1.Physiochemical Properties of Vegetable Oils

Depending on the source of vegetable oil, the corresponding biodiesel have quite unique physiochemical properties. Some chemical compositions also include fatty acid content, iodine index, glycerine, methanol content and water content. A good understanding of biodiesel fuel physiochemical properties is necessary in assessing fuel quality and likely performance in an engine. The important biodiesel properties necessary to predict the performance in a diesel engine are discussed below.

2.1.1. Iodine Value

The Iodine value represented by IV is stated in units of centigram per iodine which is immersed for every biodiesel gram (Hoekman, Broch, Robbins, Ceniceros & Natarajan, 2012). The IV is important in determining the degree of unsaturation of a biodiesel.

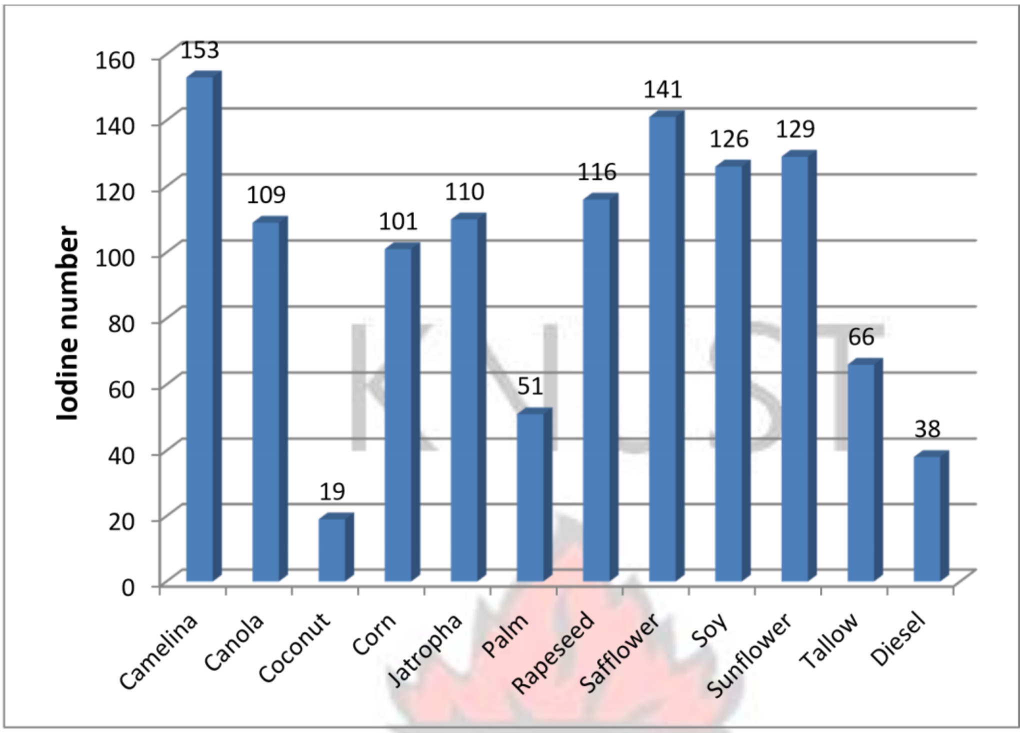


Figure 2.1 Iodine Value of Some Methyl Esters and petrodiesel (Yaakob, Narayanan & Padikkaparambil, 2014)

If the iodine value is high, then the degree of unsaturation will also be high. High degrees of unsaturation leads to oxidation reactions at high temperatures during combustion. This usually lead to irreversible polymerization (Fazal, Haseeb & Masjuki, 2010). Polymerization will cause O-rings, seals and other components to dissolve resulting in leakages and contamination. Fuels with high iodine values especially more than 50 can decrease engine life (Haseeb, Masjuki, Ann & Fazal, 2010).The lesser the iodine value, the better. Coconut-derived biodiesel is considered top quality because it is saturated highly, and had a remarkably low iodine number of about nineteen. Palm biodiesel has IV of 51 while Jatropha biodiesel reaches about 110 which are much higher than conventional Diesel IV of 38 (Figure 2.1).

2.1.2. Cetane Number

The Cetane number (CN) indicates fuel quality used in Compression Ignition (CI) engines. Though dimensionless it has an indirect relationship with ignition delay (ID) time. Ignition delay is the time that passes between fuel injection and start of ignition. An ID which is short matches to a high CN and the reverse is also true. If the duration between fuel injection and commencement of the ignition takes too long, there will not be a constant combustion. Serious gas vibrations are created that cause a strong diesel knock. In mixture engines (gasoline engine), knocks occur if the mixture burns too quickly and in diesel engines, if the mixture does not burn quickly enough. For this reason, the self-ignition temperature and the ignition quality (ignition sensitivity) are important characteristics of the diesel fuel. A fuel with higher cetane number will ignite at lower temperatures and have brief ignition delay. A higher cetane rating therefore gives a smaller ignition delay. However, extreme values of CN results in misfiring and cold starting (Innovam, 2007). The appropriate cetane range of diesel engines is between 40 and 60.

Some researchers have confirmed that hydrocarbons which are saturated with straight chains have high CN when compared with than branched chain hydrocarbons (Rao, 2011; Bamgboye & Hansen, 2008). The longer the carbon chains of a fatty acid, the more the fatty acid is likely to be saturated with a high cetane number (Demirbas, 2008). It has also been established that a change in the oxidation level will have an effect on the cetane number of biodiesel (Bamgboye & Hansen, 2008).This may account for the changes in CN obtained by researchers even for the same stock of biodiesel.

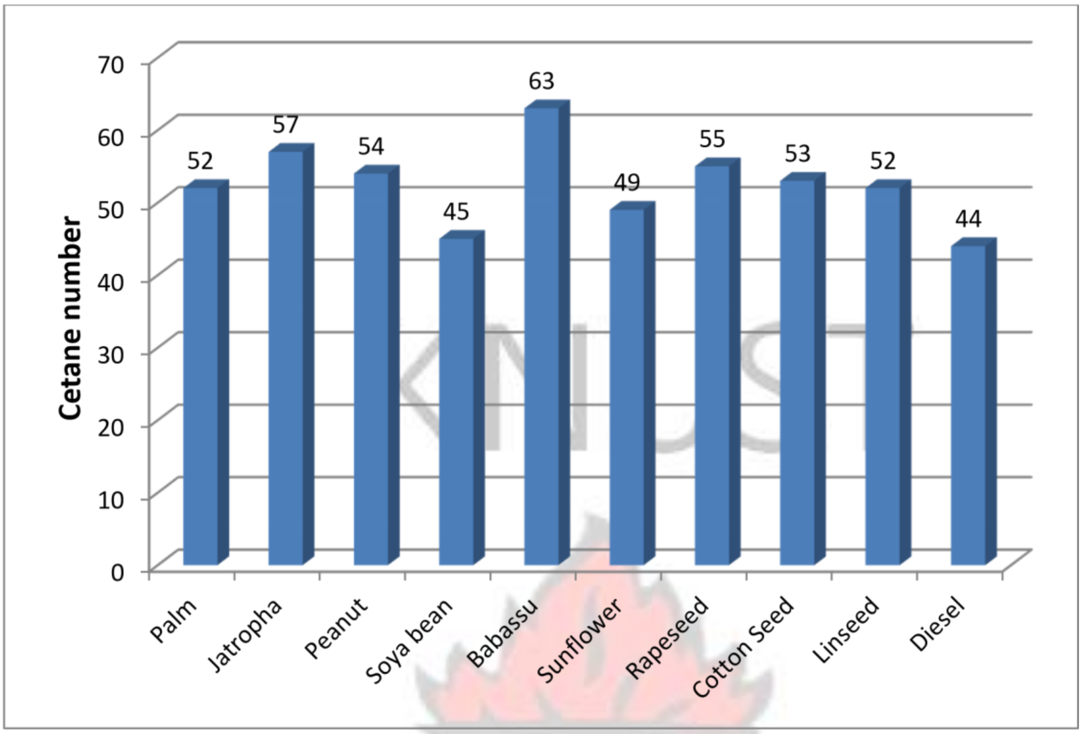


Figure 2.2 Cetane Number of some vegetable oil methyl esters (Datta & Mandal, 2016)

Since biodiesel is basically made up of long-chain hydrocarbon groups it mostly has a higher CN than petrodiesel (Figure 2.2). Sources of biodiesel rich in saturated fatty acids have higher cetane numbers (Hoekman *et al.*, 2012).

2.1.3. Calorific Value

Calorific value or heating value compares the energy content per litre for the various fuels under consideration. The element fuel composition is proportional to the calorific value.

Their values can be used to distinguish among different fuels their likelihood to produce more or less power or torque per the same volume

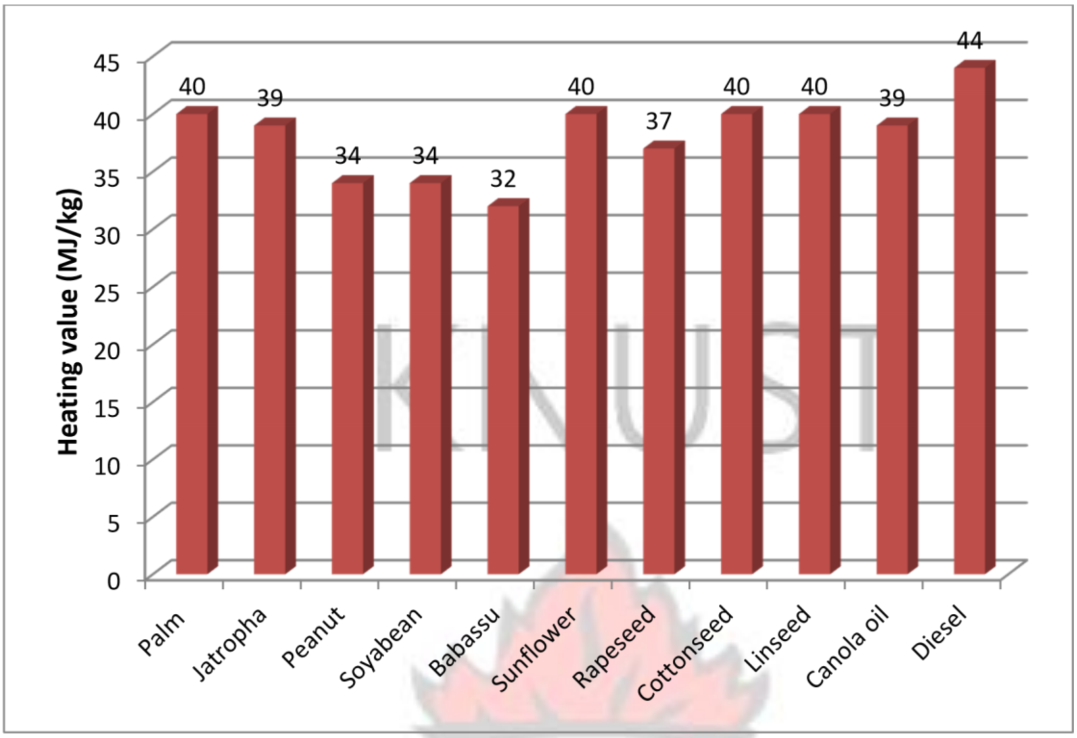


Figure 2.3 Heating Value of vegetable oil methyl esters (Lin, Huang & Huang, 2009; Saleh, 2009)

Biodiesel contains more oxygen than petrodiesel. Biodiesel has up to about 10% oxygen while petrodiesel has approximately 0.3% oxygen. The combustion efficiency of any fuel with more oxygen is higher. However, the principal contributors to thermal energy are hydrogen and carbon. Owing to high content of oxygen in, its hydrocarbons are lesser. This is what accounts for the lower calorific values of biodiesel (Figure 2.3).

This is because thermal energy is dependent on hydrogen and carbon while oxygen is ballast. The energy content of biodiesel is lower and this is attributed to its high oxygen content (Hoekman *et al.*, 2012). Except combustion efficiency of biodiesel will be higher owing to higher concentration of oxygen. This presupposes that the ideal air to fuel ratio of biodiesel will be lower compared with that of petrodiesel because lesser air will be required to burn biodiesel compared to conventional diesel (Knothe & Steidley, 2005). This is why some level of modification in injection timing, pressure, air/fuel ratio and EGR is required in a diesel engine for optimum operation of biodiesel.

2.1.4. Density and Bulk Modulus

As seen from Figure 2.4, biodiesel density is higher than petrodiesel. Any fuel with lower energy content has the tendency to produce less power per litre of fuel. As seen from Figure 2.4, biodiesel mass density is higher than petrodiesel. So for the same engine and volume, it will take a shorter time for biodiesel compared to conventional diesel to travel from injection pump to the injector. Thus, for the same volume biodiesel has a higher mass than petroleum diesel since biodiesel is known to have a relatively higher density. This is why most researchers consider biodiesel already 'chemically advanced' in terms of injection timing (Caresana, 2011).

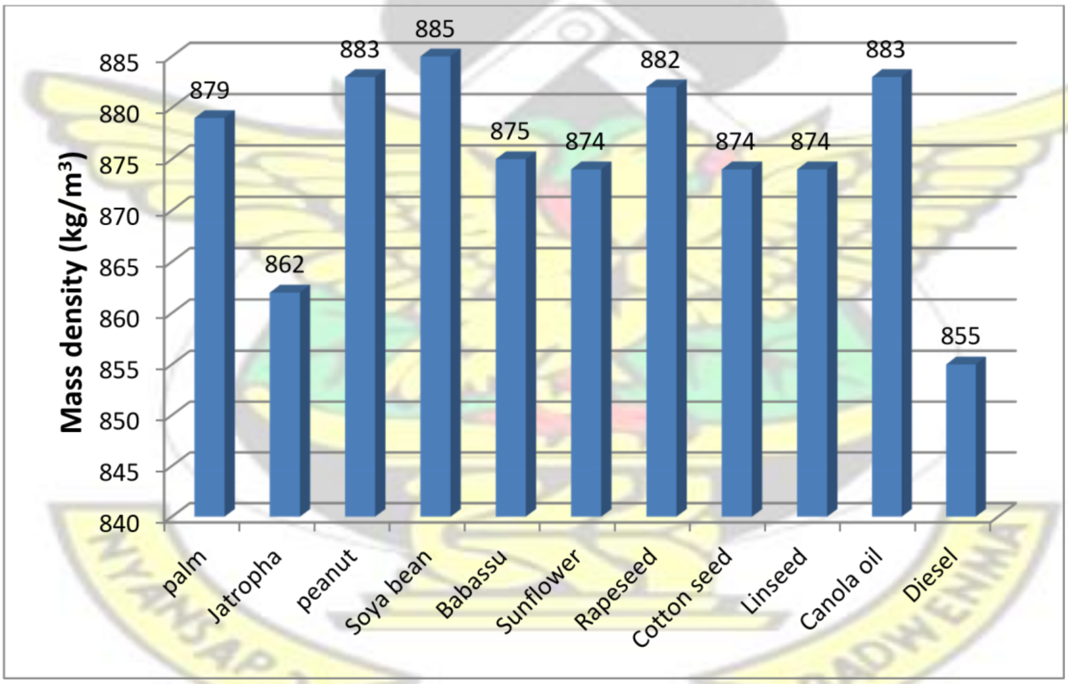


Figure 2.4 Density of various biodiesel compared with conventional diesel (Rakopoulos, Antonopoulos, Rakopoulos, Hountalas & Giakoumis, 2006)

2.1.5. Viscosity

A liquids resistance to flow owing to internal friction of molecules overreach other moving over another is termed viscosity (Knothe & Steidley, 2005). For a compression ignition engine the fuel viscosity is critical since it impacts the fuel injection components functions. For instance fuel viscosity affects injector and pump lubrication and atomization. Neither low nor high viscosity is considered favourable in a diesel engine. Some injection pumps undergo extreme wear and sometime loss of brake power attributed leak of fuel pump or injectors due to low viscosity. High viscosity of running fuel in an engine can lead to high exhaust tail pipe emissions and cause damage to the filter or pump (Rao, 2011). Poor mixing of fuel and air is believed to be caused by high viscosities of fuel (Haşimoğlu, Ciniviz, Özsert, İçingür, Parlak & Sahir Salman, 2008). Great viscosity can lead to poor evaporation (Ejim, Fleck & Amirfazli, 2007).

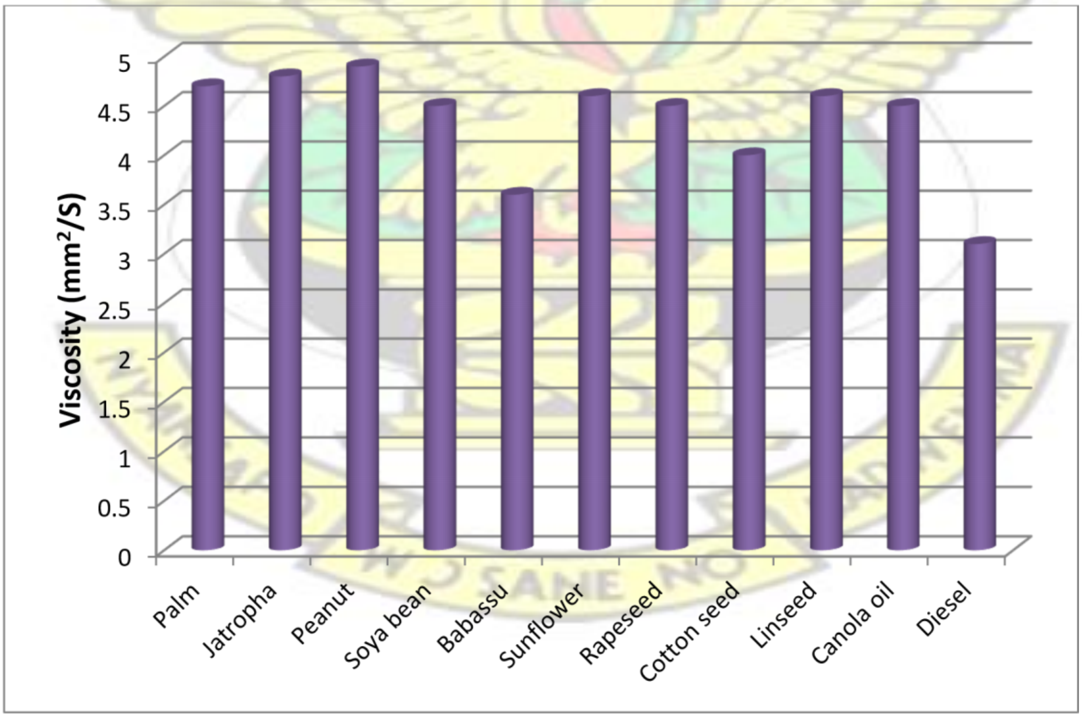


Figure 2.5 Kinematic viscosity of biodiesels and conventional diesel(Rao, 2011)

The viscosity of biodiesel as seen in Figure 2.5, is mostly on the high side relative to petroleum diesel. Viscosity is greatly affected by temperature (Knothe & Steidley, 2005). Viscosity is inversely proportional to temperature; viscosity increases with decreasing temperature and vice versa.

2.2. Compression Ignition (C.I) Engine

The C.I engine was first developed by Dr. Rudolf Diesel and was patented in 1892. The diesel engine which is the most popular CI engine has many applications in buses, trucks, tractors, locomotives, pumps, generators and marine propulsion.

The many applications stem from the fact that the running cost of C.I engine of the same capacity is lower than Spark Ignition (S.I) engine. This is because CI engines have higher thermal efficiencies than SI engines. Also diesel fuel has a higher specific gravity which makes it heavier than petrol.

Technically, as a reciprocating engines, petrodiesel engines do not use spark plugs. Thus are self-igniting at high pressures. For this reason a minimum compression ratio of 12:1 is required for auto-ignition to be possible. This is why C.I engines have higher compression ratios than SI engines whose minimum compression ratio is 6:1 (Rajput, 2007). The higher compression ratio of the C.I engine is what makes the C.I engines more efficient than SI engines. However, higher compression ratio means higher cylinder pressure requiring heavier construction. Hence C.I engines are bigger and heavier for the same power than S.I engines. The normal compression ratios for Diesel engines range between 14:1 to 23:1 while that for S.I engine range between 6:1 and 11:1.

2.2.1. Mixture Formation in C.I Engines

In the C.I engine, air is injected during air intake between 31 to 56 bar without supercharger or 80 to 110 bars for engines with supercharger. But the fuel is introduced or injected at high pressure close to end of the compression stroke (Halderman, 2012). So as soon as the fuel is injected, it is caused to evaporate by the heated air. Latent heat from the air is used to vaporize the fuel. More heat is abstracted from the rest of the surrounding air to enable ignition to take place. Once combustion begins further heat for evaporation is supplied from the heat from combustion. Further arrivals of fuel find air already heated to higher temperatures and therefore light up much more quickly. Basically the sequence for four-stroke diesel combustion is as follows:

- Intake Stroke: air is injected into the cylinder
- Compression stroke: the air is compressed increasing temperature and pressure Power stroke: fuel is finally injected and it is self-ignited
- Exhaust stroke: the burned gasses are expelled from the cylinder to the outside air (Innovam, 2007).

While air movement in the S.I engine is considered turbulent-confusion of whirls with no general direction of flow, that for C.I engine is described as an air swirl. The Air Swirl describes an orderly movement of air so as to bring continuous supply of fresh air and sweep away products of combustion (Rajput, 2007).

2.2.2. Combustion Process in C.I Engines

Combustion process for a C.I engine is sketched below in Figure 2.6. The labels are

A = injection moment pump

B = injection moment atomizer

C = start of combustion

E = end of injection

F = end of combustion

A-B = injection delay

B-C = ignition delay

C-D = creation of the flame front

B-E = total injection duration

D-E = direct combustion

E-F = after combustion

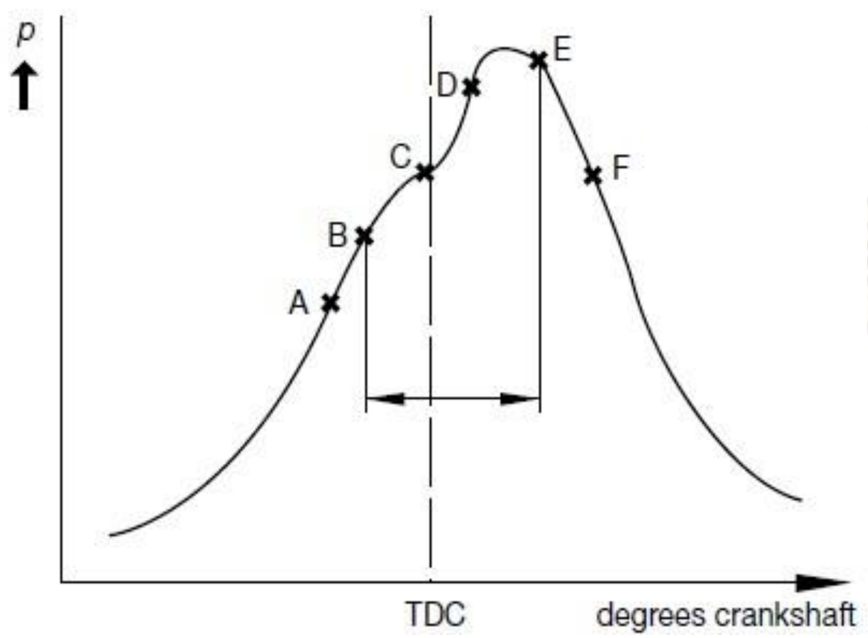


Figure 2.6 Combustion process illustration in a diesel engine (Innovam, 2007)

The **injection delay** (A-B): It is the time between injection pump activation and the beginning of the injection of the atomizer.

The **ignition delay** (B-C): is the duration between the time the first fuel particle enters the combustion chamber and the time the first fuel particle is ignited. This duration must be as small as possible. Fuel type and type of combustion chamber have been proven to affect the ignition delay.

During the period of **direct combustion** (D-E), the fuel that is injected will quickly be ignited. The course of the combustion can be controlled during this period by means of the fuel that is injected (injection pattern, quantity).

During the **after burn** (E-F), no more fuel will be injected.

2.2.3. Types of Diesel Engines

Diesel engines are in two types namely

- Direct Injection engines
- Indirect diesel engines

For a direct C.I engine system (Figure 2.7), fuel is injected directly through the atomiser as seen in Figure 2.7 below. Heat loss is small because the injected fuel travels a shorter distance.

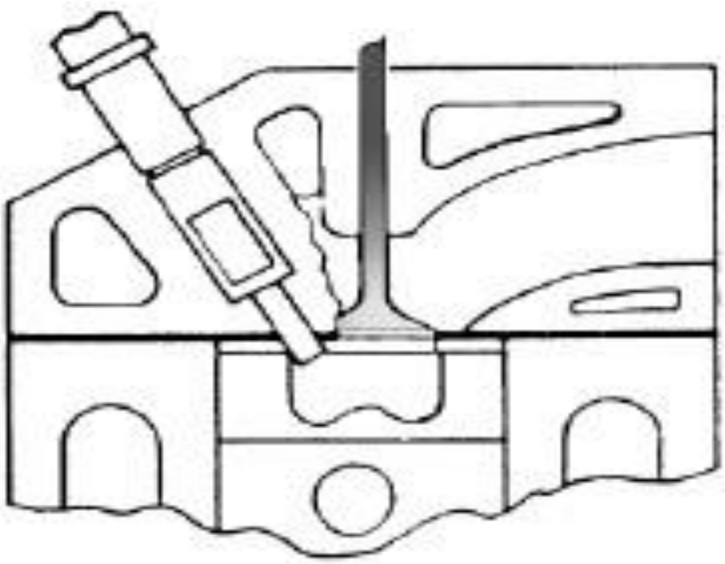


Figure 2.7 Directly injected diesel engine design (Innovam, 2007)

In the case of indirect injection, the combustion chamber is in two parts. One part is situated in the cylinder area but the second part is positioned inside the cylinder head. The section inside the cylinder head is a whirl chamber or a pre-chamber (Figure 2.8 and Figure 2.9). The fuel sprayed into the whirl chamber or the pre-chamber. This chamber is connected to the combustion chamber through an opening.

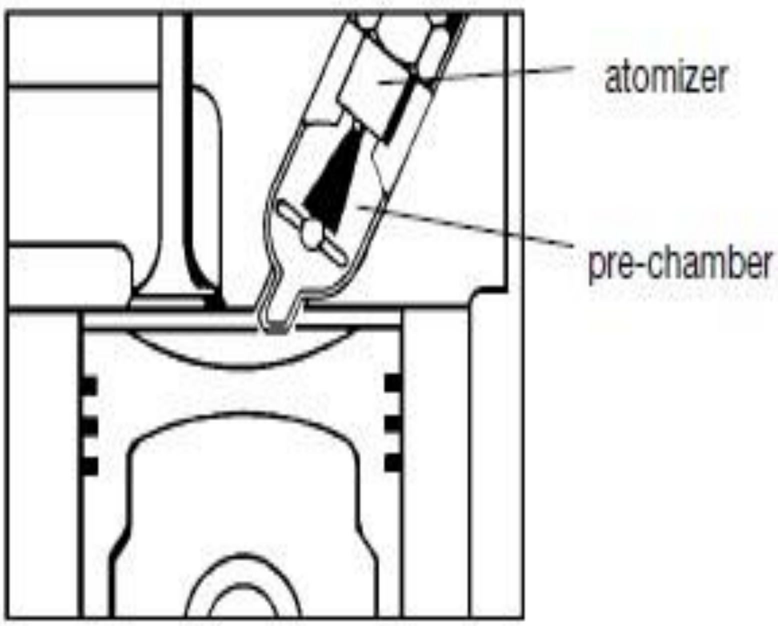


Figure 2.8 Illustration of pre-chamber type of indirect diesel engine (Innovam, 2007)

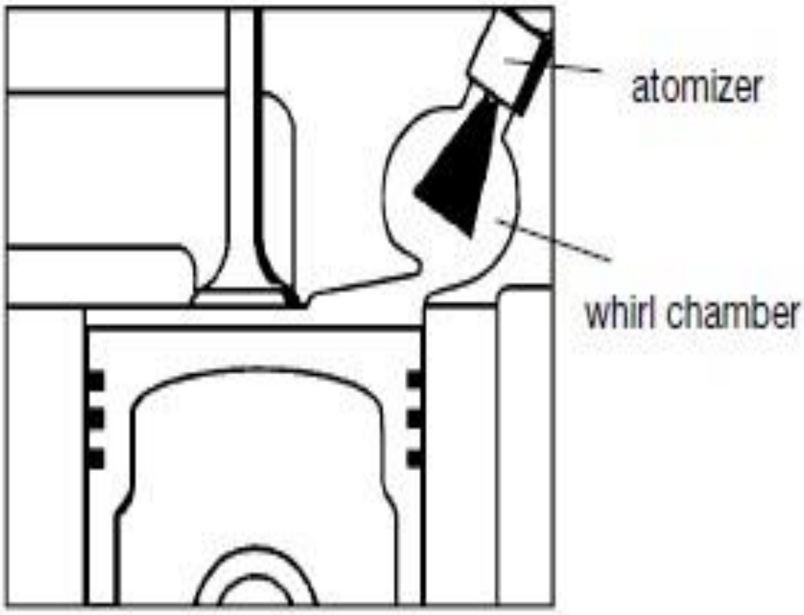


Figure 2.9 Illustration of whirl chamber type indirect diesel engine (Innovam, 2007)

With indirect injection the pre-chamber is not exposed to the same amount of heat as the main combustion chamber (heat is lost to the cylinder walls and combustion chamber walls). Indirect engines therefore need to be designed in such a way that it should overcome difficult starting when the weather is cold. A significant design difference between direct and indirect diesel engines is in their compression ratios.

Direct injection engines have compression ratios 16:1. Compression ratios of between 22:1 and 30:1 are used for indirect engines. A high compression ratio is also used in indirect injection engines to raise their thermal efficiency and economy. Unlike direct injection engines this tend to counteract the greater heat loss caused by the larger surface areas of an indirect injection combustion chamber (Hillier & Calex, 2006).

Direct injection systems have been used on larger diesel engines for many years, especially for heavy commercial applications. Since the 1980s, light passenger cars have also increasingly been fitted with smaller direct injection engines. Direct injection does mostly have one notable drawback in terms of noise. The combustion noise is considerably higher than indirect type engine.

2.2.4. Diesel Engine Management (Common Rail)

The function of the engine management system is to manage by varying the torque generated by the engine or speed. In a diesel engine, exhaust-gas treatment and noise suppression are performed to a great extent inside the engine. This is done by the engine management by changing the following variables:

- Start of injection
- Injection pressure
- Intake swirl
- Exhaust gas recirculation

With engine management, injected fuel quantity and start of injection is governed exclusively by an Electronic control unit (ECU).

Currently OEMs complain of emission legislations forcing further emissions reductions. This has made electronic control for unit injectors more popular in use.

In common rail system (Figure 2.10), high pressure petrodiesel, over 20,000 PSI. 138,000 kPa), is supplied to the injectors opened by a magnetic solenoid controlled by the an electronic control unit (Halderman, 2012).

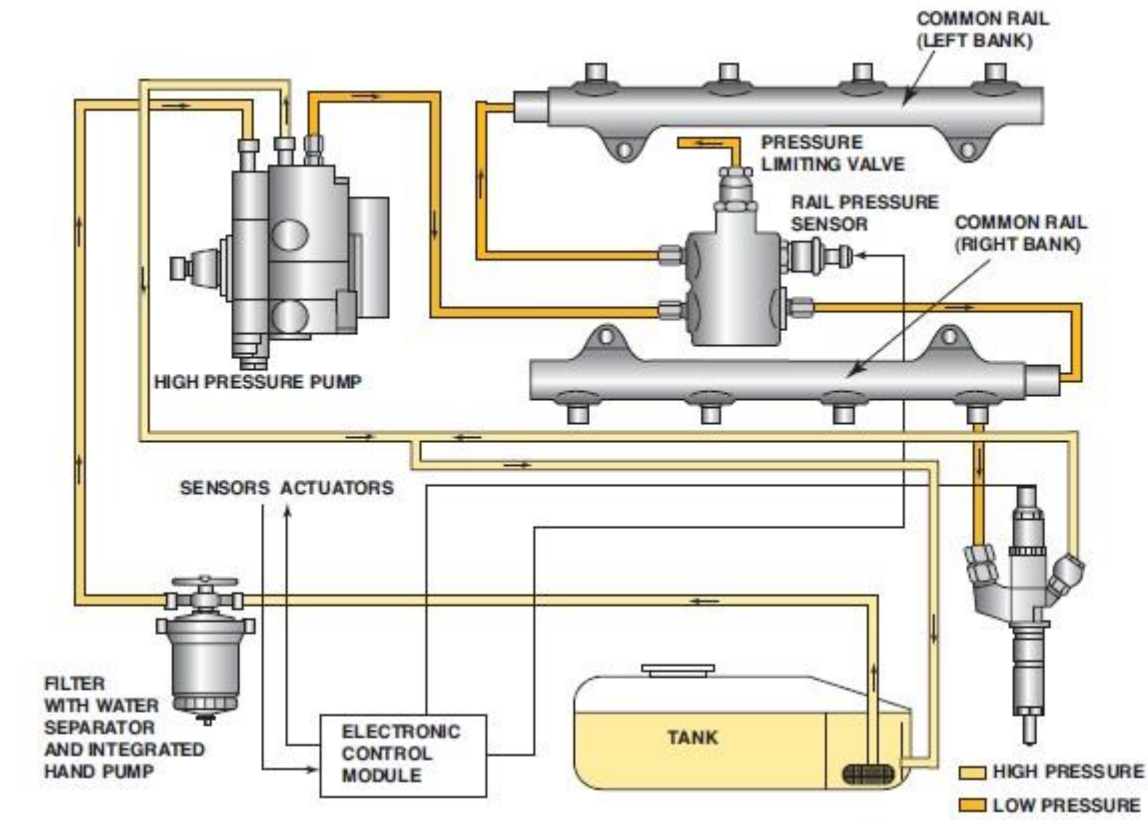


Figure 2.10 Common rail fuel injection system installed on newer diesel engines (Halderman, 2012)

An advantage of using a common rail system is the use of high pressure pumping component found near the injector. Formerly with traditional diesel fuel engine, the pumping element passes through a long tube. Such systems has the fuel pump quite a distance away from the. With a long delivery pipe carrying high pressure, when the pump delivers the fuel it causes a pressure wave to travel along the delivery pipe (which is full of fuel); the time delay in the high pressure wave reaching the injector causes timing inaccuracies of injector opening and closing. For systems without common rail, it is difficult to tell the exact injection timing.

2.3.Influence of Biodiesel on C.I Engines

The world's oil supply of oil is likely to reach its maximum production and depletion by 2020 as stated by United States department of Energy (Gumus, Sayin & Canakci, 2012). Currently, at consumption levels of 85 million barrels of oil a day, the current reserves of about 1.27 million barrels of oil can only last for the next 40 more years (Vasudevan & Briggs, 2008). The past decade has therefore seen numerous researches into performance of biodiesel usage in compression ignition engines (Xue *et al.*, 2011).

Journals articles on Fuel, Fuel Processing, Fuel Processing Technology, Energy, Applied Energy, Energy conservation and Renewable Energy have been dedicated to biodiesel research. Biodiesel sources adapted for a country commonly are chosen based on availability and abundance in the country considered. For instance, soybean United States have adapted soybean oil while rapeseed oil abundant in Europe have been adapted by most while European countries. Malaysia has heavily invested in Palm oil; most Asian countries like India however consider Jatropha.

In spite of the many research done not many advances have been made in the area of biodiesel performance in a C.I engine. No vehicle is certified by any vehicle manufacturer to run on B100. It has been suggested that fuel additives which make biodiesel less corrosive be used with biodiesel. But this is likely to escalate the price of biodiesel products. Thus it is imperative that a dedicated engine be converted with slight adjustment on fuel intake components (Jayed, Masjuki, Kalam, Mahlia, Husnawan & Liaquat, 2011). For instance, most research has determined that in the prevailing design of engines any blend beyond 20% will require a modification to the engine (Panwar, Shrirame, Rathore, Jindal & Kurchania, 2010). This is because the optimum biodiesel blend is B20. Most findings have resolved that 20% biodiesel blend for current design engines (Habibullah *et al.*, 2014; Ong *et al.*, 2014; El-Kasaby & Nemit-Allah, 2013; Mofijur *et al.*, 2013). Indeed, till date no manufacturer warrants its vehicle to operate above 20% blend. As rightly identified by the American Biodiesel Board, the 2009 Dodge Ram, 2500, and 2009 Dodge sprinter van are among the very few vehicles approved to run on B20.

Most research works agree that conventional diesel performance still outweigh biodiesel in many areas (Palash, Masjuki, Kalam, Atabani, Rizwanul Fattah & Sanjid, 2015; Wan Ghazali *et al.*, 2015; Roy, Wang & Bujold, 2013). Generally results have shown that BSFC of B100 is greater than that of petrodiesel by 10% to 12% (Gumus *et al.,* 2012). It is one of the reasons; biodiesel usage in engines is less economical than diesel. Indeed, many reviews done on biodiesel research conclude that the use of biodiesel give 3 to 16% engine power loss, 3 to 14% torque reduction and increase NOx emissions of 9 to 52% (Ong *et al.*, 2014; Kruczyński, 2013; Dhar, Kevin & Agarwal, 2012; Aydin & Bayindir, 2010; Öner & Altun, 2009). Except a few others whose biodiesel showed relatively higher brake power of about 1.5 to 14.3%, reduced BSFC of about 1.5 to 8% and reduced NOx of 5 to 14% compared to petroleum diesel (An, Yang, Chou & Chua, 2012; Panwar *et al.*, 2010; Saleh, 2009; Haşimoğlu *et al.*, 2008). It is also reported of increased power-torque values with oil methyl-ester from tall and diesel fuel blends (Altıparmak, Keskin, Koca & Gürü, 2007).

Some researchers have shown favourable results for the use of biodiesel. engine runs with biodiesel lowers emissions CO and HC but increased emissions of NOx (Nabi, Hoque & Akhter, 2009; Qi, Geng, Chen, Bian, Liu & Ren, 2009). The summary of it all is that some engine modifications are required if biodiesel, especially B100, is to compete favourably with diesel. It is overwhelming that there is a huge gap in biodiesel engine research especially in the area of engine modification (Jindal, Nandwana, Rathore & Vashistha, 2010). It is known that although biodiesel has many advantages over diesel fuel, there are several problems that need to be addressed. Such as its lower calorific value, higher flash point, higher viscosity, poor cold flow properties, poor oxidative stability and sometimes its comparatively higher emission of nitrogen oxides (Ganapathy, Murugesan & Gakkhar, 2009).

If modifications are to be made then one parameter that needs to be investigated thoroughly is the ignition timing. Injection timing has enormous influence on the performance of an engine (Kishore, Dilip, S, Satish & Deepak, 2010). In terms of power increase and thermal efficiency, it has been recommended that modifications in the engine fuel system be made. Compression ratio (Laguitton, Crua, Cowell, Heikal & Gold, 2007), injection process and parameters (Nwafor, 2007) are to known to affect efficiency and power when B100 is in use. Injection parameters have been reported to likely affect fuel consumption, power, torque and NOx formation. This is because of the different fuel properties of biodiesel, density, viscosity, bulk modulus, cetane number, oxygen content require different injection timing from that of conventional diesel (Rao, 2011; Mccormick, Ratcliff, Moens & Lawrence, 2007). Factors like injection timing, injection pressure, injection rate, compression ratios and even viscosity of fuel have been proven in literature to be affected greatly by viscosity and density. For example, differences in physical properties of fuels could change the injection mechanism, the fuel spray behaviour, the combustion performance and consequently have an effect on pollutant emissions (Payri, Salvador, Gimeno & De La Morena, 2011).

2.3.1. Influence of Injection Timing on Fuel Consumption

The influence of the timing of injection on fuel economy of some biodiesel feed stocks have been investigated by few researchers. Overwhelming majority of the researchers concluded that engine economy of an engine fuelled with biodiesel deteriorates when factory settings are not altered (Xue *et al.*, 2011). Many investigations have shown that when injection timing is retarded brake specific fuel consumption decreases before increasing (Kishore *et al.*, 2010). According to Aydin and Bayindir (2010) and (Khatri, Sharma, Soni, Kumar & Tanwar, 2010) the collective influence of high viscosity and low heating value of biodiesel than petrodiesel engine may contribute to this (Aydin & Bayindir, 2010; Kishore *et al.*, 2010).

It is well known that there is advancement of the time for injection if biodiesel is run on a petrodiesel engine instead of petrodiesel due to mass per unit ratio also density (Jindal, 2011). Typically, commencement of biodiesel injection is faster than petrodiesel owing to high mass to volume ratio and viscosity (Ozsezen, Canakci, Turkcan & Sayin, 2009). Caresana (2011) is also of the view that biodiesel from density is a little greater than that of petrodiesel fuel, because pressure created by the pump travels faster and produces early injection. Hence more fuel is injected to compensate for this.

Rao (2011) asserts that because of greater oxygen percentage in biodiesel there is actually less hydrogen and carbon, which explains its lower energy content and hence an increase in fuel consumption. Biodiesel contains approximately 77% carbon, 12% hydrogen and 11% oxygen by mass (Tat, 2011). Another view which has not yet been articulated is that the advance in ignition may also have been due to the high biodiesel cetane number. This has been confirmed as lower cetane numbers caused longer ignition delay periods and vice versa (Tat, 2011).

In terms of varying injection timing not every researcher agrees with the popular view that retard in injection timing will reduce BSFC for biodiesel. It is commonly reported that advancing the injection timing from default manufacturer sets causes brakes specific fuel consumption, carbon monoxide and hydrocarbons to reduce (Ganapathy, Gakkhar & Murugesan, 2011). Noticeably the only feedstock they considered was Jatropha. Their research enlightened the best injection timing for lower brakes specific fuel consumptions as 340 CAD with Jatropha. However, no explanation was given.

The research also did not consider brake specific energy consumption which is a better parameter for comparison of fuels. However, Pandian et al. (2011) measured BSEC. They found out that after the injection timing was advanced from 18^0 and at bottom dead centre the BSEC and tailpipe emissions like CO, HC and smoke reduced. But efficiency and NOx tailpipe surged. This is ascribed to temperature and pressure decrease in the cylinder with timing advancement resulting in delayed ignition.

The effect of injection timing on fuel consumption is still left open for discussion. Especially since not one single value of injection timing has been agreed on, there is still much room for debate. Based on the fact that different feed stocks, quality of feed stocks, methodologies prone to errors and different engines have been used it is quite obvious that the results too will differ slightly.

2.3.2. Influence of Injection Timing on Thermal Efficiency

The Brake Thermal Efficiency of biodiesel is lesser than that of conventional petrodiesel. For instance, BTE of JCME is lesser than diesel at most known injection timing and engine speed. Ganapathy et al. (2011) attributes this lower BTE to the poor mixing, volatility and combustion due to viscosity surge and lesser instability of

Jatropha biodiesel.

Retardation or advancement of ignition timing also deteriorates BTE for conventional diesel. For any compression ignition engine, the manufacturer sets the ideal injection timing to be used by the engine. Advancing the injection timing from the manufacturers set ideal timing will result in early combustion while a retardation will result in late combustion. These were the reasons attributed to worsening BTE (Ganapathy, et. al, 2011). It has been reported brake thermal efficiencies can be increased from 26.2% to 28.9% if injection timing is advanced and injector pressure increased (Narayana Reddy & Ramesh, 2006).

The influence of injection timings of 19, 23 and 27 crank angle degrees were on brake thermal efficiency were compared for hong methyl ester (Banapurmath, Tewari & Hosmath, 2008). An enhancement in brake thermal efficiency for biodiesel engine run by injection timing retardation was discovered. They recorded highest brake thermal efficiency at 260 bar since better mixing of fuel with air occurred with higher injection (Xue *et al.*, 2011).

2.3.3. Influence of Injection Timing on Emissions

Effect of injection timing on emissions has been investigated by some researchers (Sayin, Ilhan, Canakci & Gumus, 2009). Ong, proved that timing of injection and viscosity will affect vehicle tail pipe emission (Ong, Mahlia, Masjuki & Norhasyima, 2011). Reddy and Ramesh, believe injection timing and pressure reduce hydrocarbon, carbon monoxide emissions when Jatropha biodiesel is run on a petrodiesel engine

(Narayana Reddy & Ramesh, 2006).

The NOx are most dangerous tailpipe emissions. A huge main stream of works read indicate that NOx emissions increases if an engine is run on biodiesel. The increase can attributed to high biodiesel oxygen percentage. It must however be noted that, CN parameters injection do affect emissions of NOx for biodiesel (Xue *et al.*, 2011). Sayin, confirms the assertion that oxides of nitrogen creation depends primarily on high temperatures in the cylinder as well as oxygen concentration (Sayin *et al.*, 2009). It must however be noted that in Sayin et., al (2009) experimentation only on biodieselethanol blends were used as the feedstock while the method of varying injection timing was not stated.

Ong, et al., (2011) reported that oxides of nitrogen emissions reduction can be attained when injection pressure and timing is increased. Especially with engine run on Jatropha biodiesel. Some researchers also consider that reducing NO emission by advancing injection timing could come at a compromise. Retarding injection timing did result in further reduction of oxides of nitrogen (Qi, Leick, Liu & Lee, 2011). It is well proven that oxides of nitrogen always reduce when there is retardation of injection timing. Kishore et al., (2010) observed that retarding the injection timing from decreases smoke density. However, this is contradicted by Ganapathy et al., (2011) who found when the timing of injection is advanced it causes particulate matter and smoke increases for both JCME and petrodiesel usage. Their explanation was that when timing of injection is advanced there is less combustion time leading to incomplete combustion. They further explained that when the timing timing occurse earlier it causes smoke tail pipe emissions of either fuels deteriorates at any given engine speed or load. However their laboratory work only considered three engine speeds of 1800rpm, 2500rpm and 3200rpm which are not quite conclusive. But Rao (2011) found through his experimental results that the retarded injection timing instead of advanced injection timing is more significant when conducting engine runs with JCME so as to lessen NOx emission but not deteriorating other emissions or engine performance. The NOx emissions of JCME have been found to be lesser than petrodiesel at normal operating conditions. Jindal (2011) also agrees that in retarding the injection NOx emissions tends to decrease.

It has been largely reported in literature that emissions of carbon monoxide from JCME are minimal compared to petrodiesel engine tail pipe emissions at most loads and engine speeds (Labeckas & Slavinskas, 2006). This is due to the reason that the chemical structure of Jatropha depicts it has more oxygen as part of its structure. This enables more oxygen to be available during burning. After advancing injection, a significant emissions increase of hydrocarbon compared with petrodiesel is observed. An advanced timing increases combustion duration because combustion actually occurs earlier. Due to this delay there is over mixing but this is contrary to injection retardation. Retardation leads to less combustion duration leading to rich mixtures resulting in increased HC emissions. When injection timing is advanced smoke, PM, CO_2 and hydrocarbon emissions are lessened. But, at retardation of injection timing, all the emission components increase (Ganapathy, et. al, 2011).

2.3.4. Methodologies Used for Varying Injection Timing

Today's Automobile is controlled by a central ECU with many other micro controllers. This is an engine management system with sensors and actuators giving information and acting respectively. It is therefore imperative that automobile engine research considers all these options to make it easier for manufacturers to implement their results. In most cases of biodiesel engine research only one biodiesel feedstock was considered in the experimentation. Some also decided to limit the number of injection timings in their experimentation making it difficult to predict the trend. Banapurmath et al. (2008) investigated injection timings influence at 19, 23 and 27 crank angle degrees.

Almost all the researchers reviewed resorted to mechanical means for varying the injection timing. The researches narrowed on old compression ignition engines that has no engine management and does not reflect the modern automobile system. Ganapathy et al. (2011) used the spill method for injection timing settings of the e experimental engine. An adapter with a syringe needle was used to decide the spill occurrence. A rounded protractor that has a specified resolution of was connected to a pulley attached to an engine. By the use of a pointer and a protractor plate (with graduations) the spill occurrence was easily noted. The fuel injection pump usually has shims under its flange. Each time the shims were adjusted, the injection timing was varied.

In his methodology Jindal (2011) stated that his experiment was carried out on an experimental engine controlled by computers. However, for changing the injection timing the pump was fitted with a pump which had shims installed on its body. Shims have thickness 0.21 mm. Each shim is capable of either increasing or decreasing the timing by 3^0. Another short coming was that this research only considered 3 degrees advancement, normal and 3 degrees retard. It is therefore difficult to conclude on the trend of performance with other ignition timings.

Narayana Reddy and Ramesh (2006) investigated the timing and pressure of injection, rate of injection and swirl of air level on biodiesel performance using Jatropha biodiesel. Various injection timings were used by adjusting fuel pump injection position relative to the cam.

In Pandian et al. (2011) research shims under the fuel pump seat was used in adjusting injection timing. Injection timing is retarded after shims are added, and vice versa. The tank was filled with fuel so that above the testing device in the tank was 10 cm. Position of the top dead center was marked by the flywheel when the piston was brought up to the top position. Fuel reached the testing device after the flywheel was turned anticlockwise. This was done again by gently rotating the flywheel noting precisely the time when the fuel moves through the experimental hole. Then the flywheel was turned back by 5 mm to mark the static injection timing position. The manufacturer's set value was then compared with this position.

Also in most methodologies single-cylinder engines were chosen for the experimentation. Xue, et al. (2011) explains that biodiesel engine economy is influenced by engine type, injection pressure, timing, load and engine speed. Although the results may not be in doubt, single cylinder engines are hardly a true representation of automotive vehicles on our roads. Emissions, torque, power and fuel consumption values for higher number of cylinders are likely to differ from single cylinder ones. Ganapathy et al. (2011) conducted their experimentation with a single-cylinder, four stroke, air cooled, vertical, Greaves Cotton model GL 400 II A, diesel Engine. Jindal (2011) experimented on a single cylinder with 4-stroke engine rated 3.5 kW which is water cooled. This engine is usually employed in Agric farming. Also Rao (2011) chose a stationery, water cooled, naturally aspirated, 4-stroke, single cylinder, direct injection compression ignition (DI-CI) engine. Huang, experimented on single cylinder four stroke water cooled, direct compression ignition engine running on pistachios biodiesel(Huang, Wang, Qin & Roskilly, 2010).

Not all the researchers used the mechanical means to vary the injection timing. Kiplimo, used a controller (Kiplimo, Tomita, Kawahara & Yokobe, 2012). Photo interrupters attached with a controller was used to alter the timing and pressure. But the research was carried out at one engine speed (1000 RPM). Also only two ignition timings of 2^0 and 40^0 BTDC were investigated. Qi, et al., (2011) varied the injection timing and EGR using a software called ETAS INCA. ETAS INCA enables data acquisition and live recording of varying engine conditions. However their research only considered soybean oil as the biodiesel feedstock. Their emission measurements were also limited to NOx and soot emissions neglecting HC, CO and fuel consumption change with respect to injection timings. Also different engine types (direct, indirect, water cooled, air cooled) were not investigated.

It is quite clear now that a new paradigm of biodiesel engine research is needed to meet the current trend in the automotive industry. New methodologies in control and instrumentation could provide different and more accurate results.

Every research finding came up with optimum variables such as timing and pressure of injection, load, torque as well as EGR but all these parameters will have to be harnessed, put together and controlled in an ECU to enable optimum biodiesel engine performance. Modern engine research will require Instrumentation and Automation in order to be relevant to manufacturers. Numerous researches have been conducted using biodiesel blends but it is about time that more research focuses on replacing diesel completely with biodiesel.

2.4.Influence of Injection Pressure on Biodiesel Engines

Engine use with biodiesel though feasible requires some level of modification to enable the engine function at its best at higher efficiency with minimal loss and prolong engine life. The injection pressure has been established to have influence on BSFC and emissions since biodiesel already has higher density, higher cetane, lower calorific value and at least 10% more oxygen content than petroleum diesel.

2.4.1. Influence of Injection Pressure On Fuel Consumption

Brake specific fuel consumption, BSFC, trend with varying injection pressures was investigated by very few researchers. Celikten and Gumus, disagree on the BSFC trend

(Gumus *et al.*, 2012; Çelikten, Koca & Ali Arslan, 2010). While Celikten et al (2010) found out that fuel consumption will surge except at low engine speedsre up to 1000 rpm. Gumus et al., (2012) states that at all fuel blends there is a decrease in BSFC. They attribute the decrease to the more effectual operation of the fuel at pressures of between 18 to 24 MPa. This is because of improved mixing linked with minor interval in admission caused by needle lift pressure. This leads to lesser fuel entering the cylinder. The contrasting results maybe because the former considered pressures of 250, 300 and 350 bar while the latter considered 180, 200, 220 and 240 bar. According to Jindal et al., (2010) a compression ratio increase also increases the cylinder pressure which improved the performance of the engine which they studied. Pandian, et al., (2011) have confirmed this too by observing that advanced pressure of injection reduces BSEC (Brake specific energy consumption) and increases BTHE. They have also confirmed just like most researchers on this subject that carbon monoxide, hydrocarbons and smoke opacity is reduced when injection pressure is increased.

This is so because as pressure of injection is increased there is better fuel mixing leading to quicker evaporation and enhanced reaction (Choi & Oh, 2012). Combustion is enhanced by better fuel mixing this contributing to higher brake thermal efficiencies with low brake specific energy consumptions, carbon monoxide and hydrocarbons.

2.4.2. Influence of Injection Pressure on Thermal Efficiency

There is however a consensus by researchers that increasing injection pressure results in decreasing smoke opacity and carbon monoxide (Gumus *et al.*, 2012). According to Puhan, there is increased thermal efficiency at lower pressures (Puhan, Jegan, Balasubbramanian & Nagarajan, 2009). But at lower pressures, other emissions such as Nitrogen Oxide and HC increase. However according to Puhan et al., (2009) at higher injection pressures unburnt hydrocarbons also increase. The explanation for this is that fuel droplet moves faster with a higher velocity when pressure of injection is increased. This leads to more emissions of hydrocarbons (Payri *et al.*, 2011).

2.4.3. Influence of Injection Pressure on Emissions

Not many researchers have investigated the influence of pressure of injection on characteristics of engine run on biodiesel. Also in these aspect only few biodiesel feedstocks have been researched. Çelikten, et al., (2010) examined the properties of oils of rapeseed, petrodiesel and soybean biodiesels at different injection pressures of 350, 250 and 300. They found out that fuel power-torque properties reduced with when the pressure of injection increased. Carbon monoxide and smoke emissions lessened when the pressure of injection surged except for NOx emissions. Gumus et al., (2012) also confirms, increasing injection pressure decrease smoke level, HC, Carbon monoxide, and it resulted in rise increase carbon dioxide and oxides of nitrogen emissions.

But on the contrary Puhan, et al., (2009) investigation of Linoleic linseed oil methyl ester show that oxides of Nitrogen reduces with increasing injection pressure and vice versa. Their explanation was that heating value of LOME (linoleic linseed oil methyl ester) is low and this increases the ignition delay thereby producing more NOx. However higher pressures of fuel injection makes the reduces NOx formation. The contrasting results by Puhan, et al. (2009) and Celikten, et al. (2010) may be because of the different feedstocks. Also while the former considered pressures of 200, 220 and 240 bar the later considered pressures of 250, 300 and 350. The former used a direct injection engine which had only a single cylinder while the latter experimented on a direct injection engine with four cylinders.

2.4.4. Methodology of Fuel Injection Pressure Variation

Methodologies used by the researchers for varying injection pressure are mostly mechanical means. However, most researchers fail to mention their methods for injection pressure variation. The research methodologies used also lack the element of reasoning behind the chosen methodologies. For instance Celikten et al., (2010) investigated using varied timings of 350, 250 and 300 bar but failed to mention the reasons why these particular pressures were chosen. Puhan et al., (2009) also chose 240, 220 and 200 bar as parameters for the pressures of injection but gave no reasons. Jindal et al., (2010) considered 150, 200, 250 bar with no reasons. At 180, 200, 220, and 240 bar. Pandian et al., (2011) carried out their investigations. The modern automobile operates at numerous injection pressures therefore the pressures investigated are inadequate and may not reflect the actual conditions on the road.

Jindal et al., (2010) conducted the engine tests on performance per IS: 10,000 [P: 5]:1980. Tests performances were carried out at three injection pressures (150, 200, 250 bar.

In Pandian et al., (2011) research of Biodiesel, derived from pongamia seeds, the experimentations were planned using a statistical tool based on RSM. The experimentations were steered on a naturally aspirated, double cylinder petrodiesel engine. A BOSCH standard nozzle tester was used to measure the fuel pressure between 0 to 400 bar. The injection pressure too was measured at five levels betwee 250 bar to 150 bar in divisions of 25 bar. No reasons were given for the particular choice of pressures varied. Although the automobile engine operates at several engine speeds this research focused on only 1500rpm and no reasons were given for this choice of engine speed. At only 2200 rpm constant engine speed Gumus et al., (2012) conducted their experimentation. The default manufacturer's ideal pressure of injection is 20 MPa. The thicknes of washer between nozzle and spring injector, is

0.20 mm. addition of every washer increased the injection pressure by 2 MPa. Experiments were carried out at four different injection pressure values (18, 20, 22, and 24 MPa) with decreasing or increasing washer number. Engine loads of 12.5, 25, 37.5 and 50 kPa were used but a constant engine speed of 2,200 rpm was chosen. However, method of injection pressure variation was not stated. The engine used also had no engine management system and therefore application of the results in modern engines is questionable.

Mostly single cylinder engines were used for the experimentations. Puhan et al., (2009) also used a small engine hardly used on roads.

2.5.Nitrogen Oxide Emission from Biodiesel Engines

Nitrogen Oxides (NOx and NO) is considered dangerous as far as engine emissions are concerned. The reduction of it is always the target for engine researchers and engine manufacturers. Nitrogen oxides are known to be created at a high temperature and an excess of oxygen (air). Oxides of nitrogen creation primarily relies on high temperatures and reaction time (Gumus *et al.*, 2012).

EGR is utilized in petrodiesel engines in order to limit the quantity of nitrogen oxides (NOx) present in the exhaust gases (Innovam, 2007). The EGR is calculated as a ratio of exhaust gas mass divided by inlet intake exhaust mass. It is varied between 0% to 45%. The creation of nitrogen oxides can be countered by decreasing the combustion temperature and/or by reducing the amount of oxygen in the combustion chamber. EGR, is a technique widely used to control NOx emissions especially in compression ignition engines fuelled by petrodiesel. The technique controls NOx formation by reducing the oxygen content and temperature of exhaust that re-enters the combustion chamber (Agarwal, 2007).

The common constituents of exhaust tailpipe emissions are carbon dioxide and nitrogen. These mixture does not take part in the combustion process when re-injected because it has higher specific hear relative to normal air from the atmosphere. The reinjected air from the exhaust replaces the fresh air with CO_2 and water vapour. Since some of the fresh air has been replaced with exhaust gas, only a small portion of oxygen will be available for combustion. This affect the air to fuel ratio by lowering it which has implications on exhaust tail pipe emissions. Also the effective temperature of the re-entered air is reduced since specific heat of exhaust gas is lower through cooling in the EGR. The interactive effect of low oxygen in the re-entered air as well as low temperature is what reduces NOx formation (Agarwal, Gupta & Kothari, 2011). Because the exhaust gases contain little or no oxygen, they do not participate in the process of combustion. The exhaust gases are however heated during the combustion process, which causes the average temperature to decrease. The quantity of exhaust gas that participates in the recirculation needs to be controlled. If too many exhaust gases are fed to the inlet system, the hydrocarbon, carbon monoxide (CO) and pm emissions will rise.

In modern Automobiles, the control unit calculates how much exhaust gas may be added to the inlet gas. This takes place on the basis of the operating condition of the engine (air quantity, fuel quantity, rpm's, engine temperature). On the basis of operating conditions, the control unit directs the control valve for the exhaust gas recirculation (EGR control valve). The EGR control valve operates the vacuumoperated recirculation valve (EGR valve). The EGR valve allows a certain quantity of exhaust gas to the inlet air temperature manifold. Depending on the signal of the control unit, the EGR control valve ensures more or less vacuum above the EGR valve membrane. This causes the EGR valve to be opened more or less.

The ideal ratio of air to fuel for biodiesel is lesser than petrodiesel fuel and this is linked to the about 10% biodiesel oxygen composition. Stoichiometric air/fuel ratio of diesel (HC) is 14.86 while that of a typical biodiesel such as jatropha is 13.9 (Rao, 2011). Which implies that biodiesel will require less oxygen than diesel to burn ideally. It also means the EGR control algorithm for diesel will not be ideal for biodiesel. If conventional biodiesel is to be completely replaced by biodiesel the EGR control algorithm will have to be altered.

2.5.1. Reasons For NOx Increase In Biodiesel

Due to higher sound velocity and lower compressibility, biodiesel pressure by the injection pump is faster when injected. Thus, an earlier needle opening is noticed when biodiesel fuel is run in a diesel engine. This increases temperatures in the combustion chamber leading high oxides of nitrogen formation and emissions (Celikten et al., 2010).

It is overwhelmingly supported by researchers that NOx emissions rise with increasing percentage of biodiesel in a diesel-biodiesel blend fuel. Even though some biodiesel produces more NOx than others.

2.5.2. Influence of Exhaust Gas Recirculation on Biodiesel Performance

Qi et al (2011) investigated EGR and injection timing to identify the most effective combination. It was discovered that the best methods to lessen oxides of nitrogen emission was to increase EGR rate and retard main injection timing. When the exhaust gas recirculation rate was increased by 5%, oxides of nitrogen emissions were reduced by about 50%. However, this favourable NOx emission is at the expense of other emissions. Engine speed, power output and torque are decreased with increasing EGR. Qi et al., (2011) explained that a unit of fresh air is displaced and replaced with an equal amount of combusted exhaust with exhaust gas recirculation operation. This affects air to fuel ratio of the engine.

On the other hand, Saleh (2009), obtained a reduction in NOx and BSFC (increased fuel economy) with growing exhaust gas recirculation rate up to 5% at 25% load (Saleh, 2009). They attributed this to rise in thermal efficiency owing to incomplete combustion of hydrocarbons leaving some unburnt in the exhaust. These confined to the EGR do burn again in the mixture, reducing the unburnt hydrocarbons in the exhaust. Pradeep and Sharma (2007), compared biodiesel with EGR and diesel with EGR (Pradeep & Sharma, 2007).

Most researchers agree that low boiling point, calorific value and viscosity can be attributed to this. Some researchers also report that higher BSFC and particulate emissions are observed with EGR application (Çelikten et al., 2010). In addition to BSFC increase some researchers have also reported increase in carbon monoxide levels as EGR rate surged.

Exhaust gas recirculation of between 20 and 25% showed in bad performance and immense particulate matter (Pradeep and Sharma, 2007). In spite of its potential to reduce NOx emissions there are still many disadvantages associated with EGR usage.

However, EGR increases the hydrocarbon and carbon monoxide emissions. This is as a consequence of lean mixtures caused by too much mixing (Kiplimo *et al.*, 2012). EGR usage can disturb lubricating oil quality and engine durability (Çelikten, et al. 2010). Some research studies have shown that deposits of high soot formed found on the injectors piston, cylinder head and crown of engines fitted with exhaust gas recirculation. This was not the case for engines without exhaust gas recirculation.

2.5.3. Methodologies for EGR performance with Biodiesel

Very few research works have been done on EGR operation with biodiesel. Even those done considered only Jatropha, jojoba, rapeseed and soybean oil only. Celikten et al., (2010) in their comparison of biodiesel emissions considered soybean and rapeseed oils. Qi et al., (2011) used soybean oil to compare EGR operation while Saleh (2009) experimented on Jojoba Methyl Ester.

Many studies on biodiesel were done with smaller petrodiesel engines. Saleh (2009), investigated effect of a two-cylinder direct compression ignition engine with EGR which is water cooled and four stroke cylinder. For Agarwal et al., (2011) a twocylinder constant speed diesel engine generator set was chosen to study the effect of EGR on the performance and emissions, carbon deposits, and wear of diesel engine components. Kiplimo et al., (2012) chose a single-cylinder test engine.

The methodologies used so far on biodiesel EGR research have not varied engine speed to synchronize real road conditions. Results obtained therefore can be attributed to only one engine speed. For instance, Saleh (2009) experimentation hold true only for engine speed of 1600 RPM. Kiplimo et al., (2012) mentions they performed all the experiments at constant engine speed.

Mostly all the methodologies for EGR variation have been by manual installation. Some had to install new EGR systems since the original engines were without them.

Unfortunately, these EGR systems do not reflect the engine management systems (controlled by Control Units) used on modern automobiles. In some other methods, the exhaust manifold is connected to an intake manifold whereas the EGR is in between this connection. This links the exhaust manifold with the intake manifold. There is also a pressure tank with filter bag, an exchanger and exhaust gas recirculation valve.

Reduction in particulate matter and production of gas is regulated by a bag filter. Exhaust pressure pulse is reduced by the pressure tank while exhaust cooling is undertaken by exhaust cooler which operates using a water flow. Exhaust gas intake flow is manually regulated by an EGR valve and is also used to attain alternative exhaust gas recirculation ratios.

Agarwal, et al., (2011) added an insulated pipe hose to allow re-entered gasses from the exhaust to be cooled partly. The control of exhaust quantity of EGR was done by a valve control. So as to quantity rate of flow of gases that had re-entered an opening was mounted in exhaust gas recirculation loop. Air flow intake rate was measured using a steady flow equipment. Fuel consumption meter was used in the measurement of fuel consumption.

2.6.Material Compatibility with Biodiesel

Only few works can be found in literature with detailed studies of biodiesel durability with automotive materials (Kumar, Varun & Chauhan, 2015; Shahir, Jawahar & Suresh, 2015; Yang, Chien, Lo, Lan, Lu & Ku, 2007).

In durability tests, the engine is run for longer hours, between 300 to 1000 hours. Intermittently during and after the run lubricants and engine components are examined visually. Lubricant analysis technique, which examines the lubrication oil for traces of wear and contamination with other oils, seals and O-rings, is often used.

Table 2.1 below depicts the various aspects of the Diesel engines and materials their made off.

Table 2.1 injection, storage and exhaust systems and their material constituents in automotive vehicles (Haseeb et al, 2011)

PART	COMPONENT	COMMON MATERIALS

Fuel tank	Housing Gasket	Steel, plastic, paint, coating, elastomer, paper, cork, copper
Fuel feed pump		Aluminium alloy, iron based alloy, copper based alloy
Fuel lines	High pressure line Low pressure line	Steel plastics, rubber
Fuel filter	Filter cartridge Housing	Paper Aluminium, plastic
Fuel pump		Aluminium alloy, iron based alloy, copper based alloy, stainless steel
Fuel injector		Stainless steel
Cylinder	Cylinder head Cylinder barrels Cylinder liner valves	Gray cast iron, cast aluminium, forged aluminium Gray cast iron, steel, cast aluminium Gray cast iron, aluminium Steel casting
Piston assembly	Piston Piston pin Piston ring	Sand-cast aluminium, diecast aluminium, forged aluminium, grey cast iron Steel aluminium alloy
	Bearing Connecting rod	
Exhaust system	Exhaust manifold Exhaust pipe Catalytic converter Muffler	Cast iron Steel Stainless steel, ceramic fibre, aluminium fibre Steel

The compatibility of conventional diesel with automotive components has no known issues. However, compatibility of biodiesel with such components is yet to be established.

As far as alternative fuels are concerned, the areas of the vehicle that are under consideration in terms of material compatibility include the injection, fuel and exhaust systems illustrated in the table above.

Biodiesel, no matter the source of feedstock, is considered to have a far better lubricity than that of diesel fuel. Unfortunately, in long term test it loses its lubricity due to its oxidative and corrosive nature (Fazal, Haseeb & Masjuki, 2011). It is reported that biodiesel which is oxidized is very corrosive (Haseeb *et al.*, 2010). McCormick et al (2007) also confirm that after 4-8 weeks of storage, biodiesel oxidize storage tanks, pipes and diesel engine parts. Oxidization is well known to precipitate corrosion. It is also interesting to note that some of the storage problems of biodiesel though may depend on the type of feedstock but also depends on the preparation of the biodiesel itself. This is given credence by Bryan Moser, who discovered after 12 months of storage that only Canola oil methyl ester compared with palm, soybean and sunflower oils was affected by extended storage (Moser, 2011). Biodiesel which is not standard may contain elements such as water and sediments (Sharma *et al.*, 2008). In addition biodiesel has a likely tendency be hygroscopic and can corrode metals (Fazal *et al.*, 2010). Oxidation is the primary causative agent for corrosion (Tsuchiya, Shiotani, Goto & Sugiyama, 2006). To the extent that other researchers such have proposed that Aluminium and Copper are not compatible with biodiesel because of their ability to oxidize biodiesel by serving as catalyst (Dodos, Zannikos & Stournas, 2009). The type of feedstock contributes immensely to compatibility with automotive materials and the extent depends on the concentration of unsaturated acid (Krahl, Knothe, Munack, Ruschel, Schröder, Hallier, Westphal & Bünger, 2009). Since the level of saturation varies from feedstock to feedstock, it explains why varied results have been obtained for different biodiesel feedstocks.

Apart from its corrosiveness biodiesel has been reported to be a solvent that can dissolve layers on steel surface. These dissolved particles could clog the injection pump; a precision instrument, and filter.

Common problems found by most researchers during material compatibility and durability tests are fuel pump failure, filter plugging, injector choking, and some moving parts getting attached or sticking. Some areas of concern in biodiesel usage include corrosion, viscosity, flow properties, free methanol, esterification by products and solvency. Successful methods to overcome these problems are yet to be exhausted (Fazal *et al.*, 2011).

There is not enough material presented vehicle engine materials tolerance to biodiesel fuels (Haseeb *et al.*, 2010). The most known seal materials are polyurethane, nitrile rubber, Buna-N, EPDM, silicon rubber, virgin polytetrafluoroethylene (PTFE), and aluminium. Most of these materials has been proven not compatible with biodiesel (Wander, Altafini, Colombo & Perera, 2011).

2.7. Rate of heat release of biodiesel engine

Results of P-V diagrams of biodiesel and petroleum diesel fuelled engines has been found not to have any significant difference (Tesfa, Mishra, Zhang, Gu & Ball, 2013). Tesfa et al. (2013) found out that there is no significant power difference by the engine cylinder for B50, B100 and petroleum diesel.

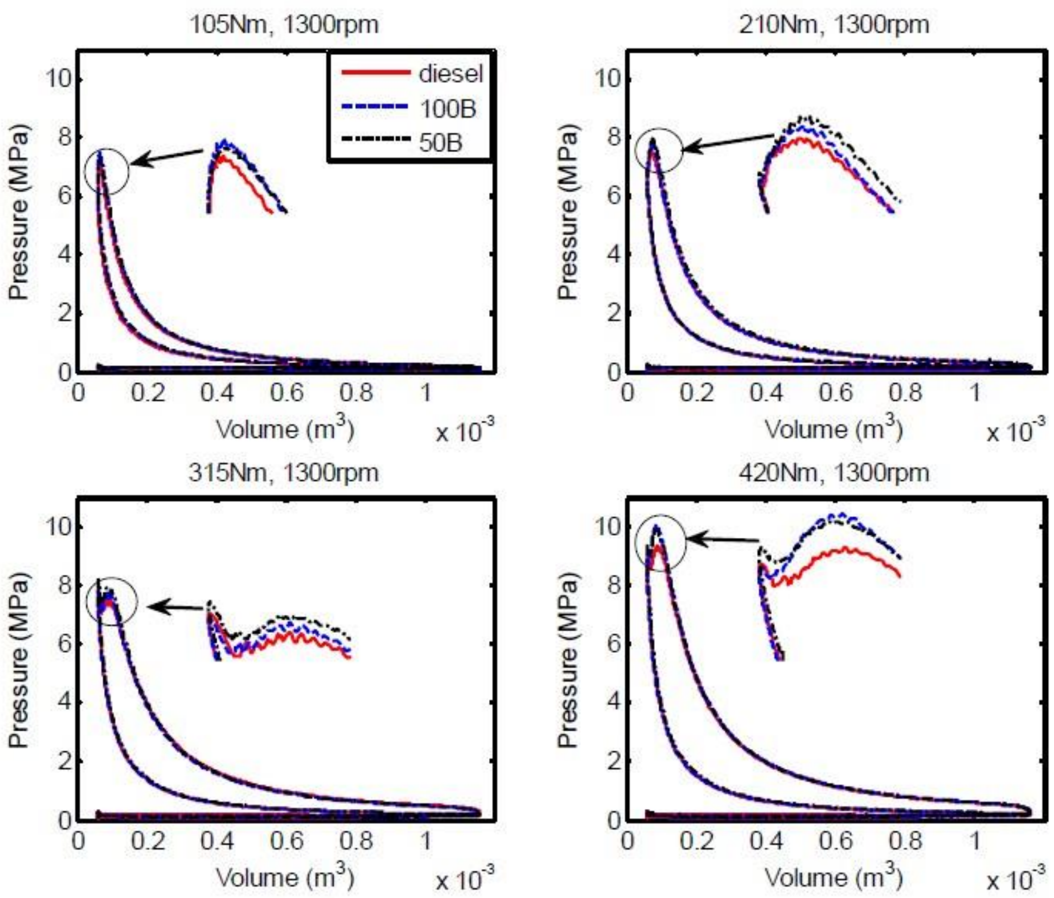


Figure 2.11 P-V diagrams of biodiesel and petroleum diesel under different working conditions (Tesfa *et al.*, 2013).

At engine loads of 105, 210, 315 Nm and 420Nm they found out it was found out that no significant power difference were observed (figure 2.11). This is because the lower calorific value of biodiesel is by combustion related effects such as high pressures and oxygen composition.

2.8.Summary of Literature

When diesel is completely replaced by biodiesel it is apparent that engine modifications are required. There is a huge gap in terms of effect of engine type (direct, indirect, pre-chamber, whirl chamber) on biodiesel usage. Some feed stocks such as palm kernel oil are also yet to receive attention from researchers. Where no modification has been applied to the engine, the injection pressure and timing of biodiesel has significant effect on brake power. It is important to investigate further the connection that exists between injection pressure and injection timing. This will enable a perfect combination of pressure and timing to be found.

A combination of injection pressures and timing coupled with exhaust gas recirculation rate to obtain optimum fuel consumption and exhaust emissions has been suggested by most researchers to be the centre of onward research (Panneerselvam, Murugesan, Vijayakumar, Kumaravel, Subramaniam & Avinash, 2015; Solaimuthu, Ganesan, Senthilkumar & Ramasamy, 2015; Caresana, 2011). They also

recommended application of instrumentation and control in EGR research. Thus, in order to use a biodiesel in a petrodiesel engine it will be better to modify some engine parameters. Petrodiesel and biodiesel have different chemical properties which makes their combustion characteristics differ as well.

Biodiesel research have focused primarily on biodiesel blends with petroleum diesel. No research has yet been sighted on biodiesel-biodiesel blends especially B100. It is also not known if biodiesel from other feedstocks when blended can affect their combined properties and engine performance. This research therefore aims to identify optimum injection timing and pressure values for the engine run on PKOME, COME and JCME. Another objective of this research is to identify if blending biodiesel of these feedstock could affect their properties and engine performance. This will identify the best blends of PKOME, COME and PKOME based on emissions and brake specific energy consumption.

CHAPTER THREE

3.MATERIAL AND METHOD

3.1.Biodiesel Production Process

There are four alternatives for making biodiesel namely microemulsion, pyrolysis, blending and alcoholysis. Transesterification is considered the best because of the lower cost and ease. No matter the mode of preparation, biodiesel production must conform to the requirements of ASTM D6751. Table 3.1 lists properties of biodiesel and petroleum diesel with their standards, respectively. Following the ASTM standards, biodiesel fuel of repeatable quality sufficient to be used for testing was produced.

Table 3.1 Petroleum diesel and Biodiesel standards

Properties	**Petroleum diesel**	**Biodiesel**
Standard	ASTM D975	ASTM D6751
Composition	HC[a] (C10-C21)	FAME[b] (C12-C22)
Boiling point (^{0}C)	188-343	182-338
Sulphur (wt %)	0.05	0.05
Cetane number	47 min	51 min
Pour point (^{0}C)	-15 to 6	-
Cloud point (^{0}C)	-	-
Flash point (^{0}C)	93 min	120 min
High calorific value (MJ/kg)	-	35
Acid value (mg KOH/g)	0.5 max	0.5 max
Density (kg/m^3)	880	860-900

3.1.1. Materials

Biodiesel was produced through the process of Transesterification according to the ASTM D6751 standards which is explained in Table 3.3. This was carried out through a laboratory scale experiment. The materials used include

1. Flat bottom reaction flask (250 ml) with three necks to contain the oil
2. Scilogex MS-H-S Magnetic stirrer with hot plate was used. It had two separate regulators for regulating heat and stirring rate respectively
3. Electronic Beam Balance with 200 g min. and 6000 g max.
4. Reaction ingredients for the (Trans) esterification include 99.8 % methanol, NaOH, 98% sulphuric acid.
5. Other instruments used include Separating funnel, 8000 ml beaker, Spatula, Filter paper, Graduated eye dropper, Graduated syringe and pipette

6. Feed stocks considered for testing are oils from Palm kernel, Coconut and Jatropha

3.1.2. Experimental Procedure-Transesterification parameters

The procedure was carried out according to the ASTM standards which ensures both safety and quality of the biodiesel product. The standard ensures complete reaction, removal of all free fatty acids as well as removal of all glycerol and traces of catalyst and excess alcohol. The biodiesel produced in the laboratory was acceptable according to the ASTM D 6751 standards.

3.1.2.1.Transesterification procedure

The procedure below was carried out for all vegetable oils Palm kernel, coconut and Jatropha considered in this work.

An alkaline-catalysed esterification using NaOH to convert FFAs in coconut oil to methyl esters to reduce FFA was carried out for an hour. In the second step acidcatalysed Trans esterification was carried out where the pre-treated oil were then converted to methyl ester to further reduce FFA and hence the viscosity.

Both esterification and (Trans) esterification were conducted in a laboratory-scale experiment. The raw vegetable oil (200 g) was pre-heated for an hour to ensure removal of water as a precaution of the oil probably not being well prepared. The preheating was terminated when visual inspection showed there were no more bubbles. For all test runs for the variations, temperature was kept constant and stirring was at same speed. Methanol mixed with NaOH was added to the pre-heated coconut mixture in the flat bottom reaction flask and stirred for an hour. Test runs for NaOH and H_2SO_4 catalyst concentrations were all done at 0.6, 0.8,1 and 1.2 (w/w). The weight measurement (wt. %) was used instead of (v %) because weight gives a more precise measurement since volume changes once there is evaporation of the liquid. Methanol: oil molar ratio variations were done at 1:4, 1:5, 1:6, 1:7 and 1:8. The mixture was stirred for some time at the same rate and time for all test runs. In the second step H_2SO_4 mixed with the pre-treated blend and quickly agitated for about an hour. The essence of adding H_2SO_4 was to further reduce FFA and hence the viscosity of the biodiesel. Wet washing was then carried out with hot distilled water at 60°C and then dried to obtain the Coconut oil biodiesel. The same procedure was carried for Palm kernel oil and Jatropha oil.

Each of the procedure mentioned above was repeated for each variation of base catalyst (NaOH), acid catalyst (H_2SO_4) and methanol: oil molar ratio. The effect of base catalyst concentration, concentration of catalyst and molar ratio of methanol to oil yield of coconut, Jatropha and Palm kernel oils were studied. The yield of biodiesel obtained was calculated as

$$\text{Yield} = \frac{\text{Weight of biodiesel produced}}{\text{Initial Weight of Oil}} \times 100 \qquad (3.1)$$

3.1.2.2.Biodiesel-biodiesel blends characterisation procedure

Biodiesel of JCME and COME were blended by volume. The best blend COME was also blended with PKOME. The blending was prepared by volume. The following blends of biodiesel samples were tested for physiochemical properties:

1. 25% Palm kernel oil biodiesel and 75% Coconut oil biodiesel
2. 50% palm kernel oil biodiesel and 50% Coconut oil biodiesel
3. 75% palm kernel oil biodiesel and 25% coconut oil biodiesel
4. 100% coconut oil biodiesel

5. 100% palm kernel oil biodiesel
6. JCME and COME were also blended in the same proportions from steps 1 to 5.

Design Expert software was used to analyse the results. Design expert was chosen and the experimental matrix is as in Table 3.2.

Table 3.2 Experimental matrix from PKOME-COME blends and properties

Run	Component1 A: COME (%)	Component2 B: PKOME (%)	Response1 Calorific Value (MJ/kW-h)	Response2 Viscosity (Cst)	Response3 Density (Kg/m^3)	Response 4 Cetane Number
1	0.00	100.00				
2	25.00	75.00				
3	75.00	25.00				
5	50.00	50.00				
6	100.00	0.00				

Design Expert software version 9, a commercially available DoE tool was used for the mixture analysis of blends because of its simplicity, efficiency and popularity of use among researchers in this field. The software, a windows-based tool is owned by StatEase, Inc.

3.1.3. Fuel Testing Equipment and Measurement Systems

All biodiesel irrespective of feedstock are to be produced under ASTMD 6751 standard if the intention is to use it as fuel. Fuel tests were conducted on JCME, PKOME and COME produced under ASTM standards in Table 3.3.

Table 3.3 Biodiesel standards and procedures used for the transesterification

Properties	ASTM Standard test method	Procedure

Flash Point	ASTM D 93 Flash-Point by Pensky-Martens Closed Cup Tester (IP 34)	At least 75 millilitres are required for this test. The sample was stirred and heated at a slow, constant rate in a closed cup. At certain intervals the cup is opened so an ignition source is moved over the top of the cup. The least hotness at which the burning effects rising vapour beyond the liquid to catch fire is termed the flash point
Viscosity	ASTM D 445 -Kinematic Viscosity of Transparent and Opaque Liquids (IP 71)	A sample is retained in a capillary viscometer made of glass. The viscometer is held at a temperature that can be controlled. The duration of time needed for a specific volume of flow through a capillary by the sample is noted. This time duration is proportional to the kinematic viscosity.
Cetane Number	ASTM D 613 - Cetane Number of Biodiesel Fuel Oil (IP 41)	Diesel fuel cetane number can be measured if its ignition characteristics in an experimental engine is compared with other blends of fuels of identified cetane number. This is done by using a method called bracketing hand wheel method.
Cloud Point	ASTM D 2500 – Cloud Point of biodiesel Products (IP 219)	A sample was quickly made to cool at a determined rate and observed periodically. A hotness temperature at which a haze is first detected is termed the cloud point

Viscosity and Density measurements were made using Calibrated Capillary Glass Viscometer and Hydrometer, following ASTM D445 and ASTM D1298, respectively in Table 3.3.

Cetane Number of the three samples were measured using the Bracketing Hand Wheel procedure following ASTM D976. For all the samples Bomb Calorimeter was used to measure the Heating Values according to ASTM D 240. The methods used for some of the measurements are as presented in Table 3.3.

3.2. Injection Timing and Pressure Tests

This section explains the equipment, procedures and stages of engine optimisation carried out.

Biodiesel have quite different chemical composition compared with petroleum diesel. There are generally two types of biodiesel that are used in calculating combustion in literature. These are C19 (nineteen carbons in the chain) and the C20 (20 carbons in the chain lengths). The equation for ideal combustion of biodiesel with 19 carbons is as in equation 3.2. Equation 3.3 is the ideal equation for petroleum diesel.

$$C_{19}H_{36}O_2 + 27O_2 + 101.52N_2 \rightarrow 19CO_2 + 18H_2O + 101.52N_2 \quad (3.2)$$

$$C_{16}H_{34} + 24.5O_2 + 92.12N_2 \rightarrow 16CO_2 + 17H_2O + 92.12N_2$$
(3.3)

Equation 3.2. represents the ideal equation for the complete combustion of biodiesel with 19 carbons. It can be deduced from equation 3.2 that 3,723.22 kg of air is required to react with 296 kg of biodiesel (228 kg of Carbon + 36 kg of Hydrogen + 32 kg of Oxygen) for a complete combustion. This means 3723.22/296 = 12.56 kg of air is required for complete combustion of one kilogram of biodiesel.

Equation 3.3 which represents the ideal stoichiometric ratio of petroleum diesel indicates that petroleum diesel requires more air compared to biodiesel to obtain a complete combustion. For petroleum diesel 3378.5/226=14.95 kg of air is required for complete combustion of one kilogram of petroleum diesel. Biodiesel fuel itself contains oxygen hence requires lower oxygen to reach complete combustion. Thus, it is important to alter engine injection parameter settings in order to obtain optimum biodiesel combustion.

3.2.1. Injection parameters variation for use with PKOME and COME

Table 3.4 shows the combination of injection timing and pressures used for the experiment

Table 3.4 Experimental design matrix used for PKOME and COME injection variation

Run	**Injection Timing (CAD)**	**Injection Pressure (Bar)**	**BSEC (MJ/kW-h)**	**CO(Vol.%**	**HC(ppm)**	**NOx(ppm)**
1	-6	150				
2	-6	175				
3	-6	200				
4	-6	225				
5	-6	250				
6	-3	150				
7	-3	175				
8	-3	200				
9	-3	225				

10	-3	250				
11	0	150				
12	0	175				
13	0	200				
14	0	225				
15	0	250				
16	3	150				
17	3	175				
18	3	200				
19	3	225				
20	3	250				
21	6	150				
22	6	175				
23	6	200				
24	6	225				
25	6	250				
26	9	150				
27	9	175				
28	9	200				
29	9	225				
30	9	250				

Two engine parameters namely Timing and pressure of Injection variations and their collective effects were considered to optimize the performance of the engine in terms of emissions and fuel economy for PKOME and COME. The results were obtained through a full scale laboratory experiment described in the experimental procedure. JMP software, version 10, was used to Design the experiment and at the same time analyse the results (Table 3.4).

SAS Company invented JMP software in 1989 to help engineers to analyse data (SAS institute, 2015). JMP has many uses as statistical discovery tools, each one made to meet specific needs.

JMP is usually the most preferred software in engine optimisation. Table 3.4 above shows the Experimental design matrix used.

An experiment is generally a series of tests where deliberate variations are done as reasons for change could be observed and identified using the effect on the output. There are many strategies of experimentation including best-guess approach, response surface, and one-factor-at-a-time approach. The most common approach that has been used to do engine optimisation is considering a factor at a time methodology. The major disadvantage of this method is its inability to give effects of likely **interactions**. Interaction effects may be possible between factors. Hence if only the one factor strategy is considered the results might not reflect the truth. The best approach is to utilise the full factorial method. This is why the method of Full Factorial Strategy was chosen for this experiment though expensive. With this strategy, the collective effect of timing and pressure of injection will be noticed.

Fuel injection timing was altered at six (6) levels including a retardation of 6^0, 3^0 and advance of $6^{\ 0}$, 3^0, 9^0 CAD and the engine default considered to be 0^0 CAD. The Injection pressure was altered at five (5) levels between 150 to 250 bar in steps of 25 bar.

Responses include

- Brake specific energy consumption (BSEC)
- Carbon monoxide (CO) emissions
- Total Hydrocarbon (HC) emissions
- Oxides of Nitrogen (NOx) emissions

Engine satisfactory performance was evaluated in terms of BSEC and the following equation was used:

$$BSEC = \frac{\text{Higher Calorific Value} \times \text{Fuel Consumption}}{\text{Output Power}} \quad (3.4)$$

BSEC is used to compare the efficiency of energy consumption of fuels. It is a better parameter compared to BSFC in analysing the engine performance with different calorific values. Brake specific fuel consumption is the quantity of fuel for developing a unit power in a unit time. Only the effect of fuel density is considered in BSFC measurement. But when considering fuels of varying densities and calorific values it is better to consider BSEC above BSFC.

Factors varied include

- Injection timing
- Injection pressure

3.2.2. Properties of Biodiesel-Biodiesel Blends by Volume

Once the biodiesel-biodiesel blends mentioned earlier were carried out, engine runs for each of the blends were carried out to measure their impact on emissions and fuel consumption.

A design strategy of full factorial was chosen to carry emissions and fuel consumption tests for the blends of PKOME and COME mentioned in section 3.1.2. The experimental matrix is shown in Table 3.5.

Table 3.5 Effects of PKOME/COME blends on emissions and consumption

Run	Component1 A: COME (%)	Component2 B: PKOME (%)	Response1 BSEC (MJ/kW-h)	Response2 CO (Vol. %)	Response3 HC(ppm)	Response 4 (ppm)
1	0.00	100.00				
2	25.00	75.00				
3	75.00	25.00				
4	0.00	100.00				
5	50.00	50.00				
6	100.00	0.00				

3.2.3. Experimental Set-up for injection timing and pressure variations

The steady state engine test ran were carried out on a 4-cylinder, four-stroke, Indirect injection, turbocharged, VW diesel engine set-up coupled to a dynamometer as specified in Table 3.6 below.

Table 3.6 Specifications of VW engine (Indirect, 4-cylinder Diesel Engine)

Engine specification	Details
Engine make	VW Golf 3 water-cooled
Bore x Stroke	79.5x95.5 mm
Aspiration	Turbo
Rated power	142 kW

Rated speed	4200 rpm
Compression ratio	22.5:1
Injection timing	336 CAD
Injection pressure	150 bar
Fuel type/system	Diesel/Bosch
Engine size/cylinders	1.896cm^3/4 cylinders/ 4 Nozzles
Engine dynamometer	Alternator with water heaters

The performance parameters measured included brake torque, Brake power, Brake specific fuel consumption, brake specific energy consumption and fuel thermal efficiency were measured.

Exhaust gas composition was measured using AVL 5 exhaust gas analyser (Make: AVL Austria; Model: TG DiGas 5400). This analyser measures CO_2, CO, HC, NOx and O_2 in the exhaust gas. The measurement range and accuracy of the exhaust gas analyser are given in Table 3.7.

Table 3.7 Measurement Range of Exhaust Analyser

Exhaust gas analyser		
Exhaust gas	**Measurement range**	**Accuracy**
CO	0-10 % vol.	<.06 vol.%:±0.03 vol.% P0.6 vol.%:±5% of ind. val.
HC	0-20,000 ppm vol.	<200 ppm vol.:±10 ppm vol.
NO	0-5000 ppm vol.	P500 ppm vol.:±10% of ind. val.
CO_2	0-5000 ppm vol.	<.06 vol.%:±0.03 vol.% P0.6vol.%:±5% of ind.val

A Bosch standard nozzle tester (0-400 bar) with each graduation representing 2 bar was used to measure injection pressures on the nozzles. A diesel fuel injector pressure adjustment kit with a shim washer was used to adjust the pressures

3.2.4. Experimental Procedure for Injection Setting Variations

Each of the experiments explained below were replicated three times for each of the biodiesel fuels (PKOME and COME). Measurements were also taken of petroleum diesel

3.2.4.1.Injection Timing measurement

By adjusting the number of shims timing of injection values were varied (Win, Gakkhar, Jain & Bhattacharya, 2005). Several shims are located just below injection pump top plate which is used usually to adjust timing. The thickness of the shims are about 0.006 inch thick. Adding shims retard timing while removing shims advance timing. However, before adding or removing the shims it is important to first locate the engine's original injection timing. This is done as follows

1. The Top Dead Centre (TDC) position on the flywheel was located. This was done by raising to the top of the cylinder the piston. The flywheel was then marked just when the piston got to the topmost position.
2. As per the manufacturer's manual, the flywheel was turned slowly anticlockwise until the marked position in step 1 aligned perfectly with the alignment mark on the cylinder block. This determined the original static injection timing and compared very well with that in the manufacturer's

manual. The recommended fuel injection timing was 24^0 BTDC or 336^0 CAD with three shims.

3. Emissions and fuel consumption measurements were made at this injection timing at separate injection pressures of 150, 175, 200, 225 and 250 bar.
4. More shims of thickness 0.3mm were either added for retardation or removed to advance the timing.
5. The fuel injection timing was further varied at 3 and 6 angle degrees retard. Each angle the timing was retarded engine emissions and fuel consumption measurements were taken.
6. The procedure was repeated for injection advance of 3, 6 and 9 angle degrees.

3.2.4.2.Injection Pressure measurement

Fuel consumption and emissions measurements were taken at injection pressures of 150, 175, 200, 225 and 250 bar. A variable 24-Piece diesel fuel injector pressure adjustment shim washer kit was used to adjust injector pressures. This was done by placing or taking away shims under nozzle spring until the required pressures were obtained. A metric digital calliper was used to measure thickness of hardened shims needed to obtain required pressure. Bosh standard nozzle tester (0-400 bar range) with accuracy of 2 bar was used to determine the varying pressures.

3.3. Method of Analysis

The influence of each parameter was judged by using P-values.

if $P < 0.05$ it is concluded that the study results are statistically significant.

If *P* is calculated to be 0.001 or less, then the outcome is predicted to happen by only once in one thousand times in repeated tests.

- *p*-value ≤ 0.001 indicates very strong evidence against the null hypothesis, so you reject the null hypothesis
- *p*-value ≤ 0.05 indicates strong evidence against the null hypothesis, so you reject the null hypothesis.
- *p*-value > 0.05 indicates weak evidence against the null hypothesis, so you fail to reject the null hypothesis.

So typically a very low P-value is a sign of strong significance since it proves that it is very less likely of that event occurring by chance.

3.4. Summary of Methodology

In summary, six levels of experimentation were conducted. Initially biodiesel production from oils of palm kernel, coconut and Jatropha were optimised for yield and quality. The quality was considered in terms of viscosity. Effect of base catalyst NaOH, methanol to oil ration on yield were investigated

The biodiesel produced from palm kernel, coconut and Jatropha oils had their chemical properties determined and compared with petroleum diesel obtained from Tema Oil Refinery.

The engine runs of each of the feedstocks were conducted in a diesel engine at idle speeds and compared with petroleum diesel engine results emissions of oxides of nitrogen, Carbon monoxide, Hydrocarbon and brake specific fuel consumptions. Injection timing and pressure were adjusted to obtain the optimal combination of timing and pressure for each of the biodiesels from palm kernel oil, coconut and Jatropha. The optimal match were analysed base on emissions and energy consumption.

Blends of biodiesel-biodiesel of PKOME, COME and JCME were analysed to define feedstock influence on their combined properties. The analysis were first based on the blend properties such as calorific value, viscosity, density and cetane number. The blend properties were compared with petroleum diesel to compare how the blends fair when compared with other blends and petroleum diesel. Secondly, engine runs of the blends were then conducted and analysed based on results of emissions of CO, HC and NOx as well as BSEC. The blends were combined in two levels and not three. Once the first blend was analysed, the feedstock with the best property was blended with the next feedstock.

Power, BSFC and BTE analysis of each feedstock run on a diesel were measured and compared with petroleum diesel.

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

This chapter discusses all results obtained from the experimentation. Section 4.1 discusses the effect of production parameters such as Base catalyst concentration on yield, sulphuric acid concentration on viscosity, ratio of methanol to oil on yield.

Jatropha, palm kernel and coconut oil have been used as the basis of comparison. In Section 4.2 fuel property results of Kinematic viscosity, Cetane number, Pour point, Cloud point, Flash point, Calorific value, Acid value and Density for the Characterisation of PKOME are displayed. Through engine runs engine optimisation for PKOME fuelled engine were carried out to obtain the desired parameters of timing and pressure of injection for best emissions (CO, HC and NOx) and brake specific energy consumption (BSEC). The most desirable combination of injection timing and pressure is predicted using the desirability approach. As with PKOME the same parameter results are discussed in section 4.3 and 4.4 for COME and JCME respectively. Engine performance of PKOME, COME and JCME optimised engine injection setting results were compared with results of petroleum fuelled engine in section 4.5. Results of Biodiesel-Biodiesel blends of PKOME-COME and JCMECOME are discussed in section 4.6. Both their fuel properties and effect on emissions and fuel consumption are discussed as per the objectives.

4.1.Effect of Production Parameters

Over-all, the performance of the transesterification reaction is affected by a number of parameters such as type of alcohol, alcohol to oil molar ratio and water content, reaction temperature, reaction duration, and catalyst type. Further research and development is required to improve conversion and ester yield (Issariyakul & Dalai, 2014). Trans esterification parameters such as base catalyst concentration and methanol: oil ratio were varied to investigate their effect on biodiesel yield and in order to obtain optimized parameters high yield. A novel method of adding sulphuric acid in varying molar ratios was also investigated to check their influence on biodiesel viscosity. The feedstock considered include JCME, COME and PKOME.

4.1.1. Influence of Base Catalyst on yield

Selecting a catalyst for (Trans) esterification is very important in deciding the result of biodiesel production process but this is reliant on the source and quality of feedstock. For the production of the biodiesel (PKOME, COME and JCME) transesterification of base catalyst was done with a 6:1 molar ratio of methanol to oil at 50^0C for 2 h. NaOH catalysed (Trans) esterification of biodiesel were investigated by varying NaOH concentrations as shown in Figure 4.1. The molar ratios varied are 0.6, 0.7, 0.8, 0.9 and 1.

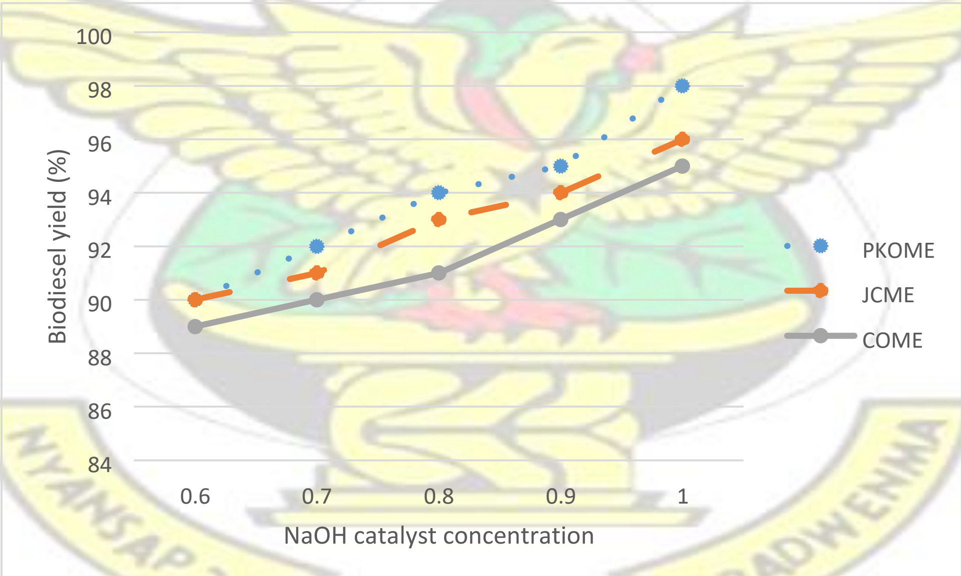


Figure 4.1 Influence of Catalyst Variation on Biodiesel Yield

For each of the feedstock, the biodiesel yield increased with increasing catalyst concentration. The highest yield was obtained with 1% catalyst concentration for all.

At 1% NaOH concentration a yield of 98%, 96% and 95% for PKOME, JCME and COME respectively at 6:1 methanol: oil ratio. This shows that the optimum conditions for NaOH catalysed (Trans) esterification required more catalyst.

4.1.2. Effect of Sulphuric Acid on Viscosity

Effect of sulphuric acid on viscosity of PKOME and COME was investigated as described in the experimental procedure. For these experiments three runs of the same experiment were conducted for all feedstock and the average found as displayed in Tables 4.1, 4.2 and 4.3.

Table 4.1 Viscosity of PKOME for varying concentrations of H_2SO_4

H_2SO_4 (wt. %)	Viscosity of Experimental Runs (mm^2/s)			Average Viscosity (mm^2/s)
	Run 1	Run 2	Run 3	
0	5.7	5.8	5.7	5.7
0.6	5.1	5.0	5.1	5.1
0.7	4.8	4.8	4.8	4.8
0.8	4.5	4.6	4.6	4.6
0.9	4.1	4.2	4.2	4.2
1	3.7	3.6	3.7	3.7

The results depict that a rise in the sulphuric acid concentration causes more favourable result as the Kinematic viscosity of PKOME was reduced from 5.7 mm^2/s to 3.7 mm^2/s when sulphuric concentration increased from 0% to 1%(Table 4.2).

Table 4.2 viscosity of COME for varying concentrations of H_2SO_4

H_2SO_4 (wt. %)	Viscosity of Experimental Runs (mm^2/s)			Average Viscosity (mm^2/s)
	Run 1	Run 2	Run 3	
0	3.9	3.8	3.9	3.9

0.6	3.6	3.4	3.8	3.6
0.7	3.3	3.2	3.2	3.2
0.8	2.9	2.8	2.9	2.9
0.9	2.6	2.6	2.7	2.6
1	2.4	2.4	2.4	2.4

The effect was even more profound with coconut oil methyl ester as addition of 1% H_2SO_4 reduced the viscosity from 3.9 mm^2/s to 2.4 mm^2/s (about 40% reduction). The viscosity reduced steadily as the sulphuric acid concentration was increased (Table 4.2).

Jatropha methyl ester experienced a viscosity reduction of 24% (4.1 to 3.1 mm^2/s) with the addition of 1% sulphuric acid (Table 4.3). The favourable effect of sulphuric acid on the viscosity may be due to the fact that the acid further acts as a drying agent drying any remaining water and dissolving any remaining free fatty acid.

Table 4.3 viscosity of JCME for varying concentrations of H_2SO_4

H_2SO_4 (wt. %)	**Viscosity of Experimental Runs (mm^2/s)**			**Average Viscosity (mm^2/s)**
	Run 1	**Run 2**	**Run 3**	
0	4.1	4.1	4.2	4.1
0.6	4.1	4.0	4.0	4.0
0.7	3.9	3.8	3.8	3.8
0.8	3.7	3.7	3.6	3.7
0.9	3.4	3.3	3.4	3.4
1	3.1	3.1	3.2	3.1

In Table 4.4 a comparison is made between the optimised viscosities obtained for PKOME, COME and JCME in this work and that obtained in literature. By the addition of sulphuric acid to the biodiesel preparation process viscosities were significantly reduced. Viscosity of palm kernel biodiesel was reduced by 22.9 % while coconut and Jatropha oil biodiesels were reduced by approximately 41% and 46 % respectively.

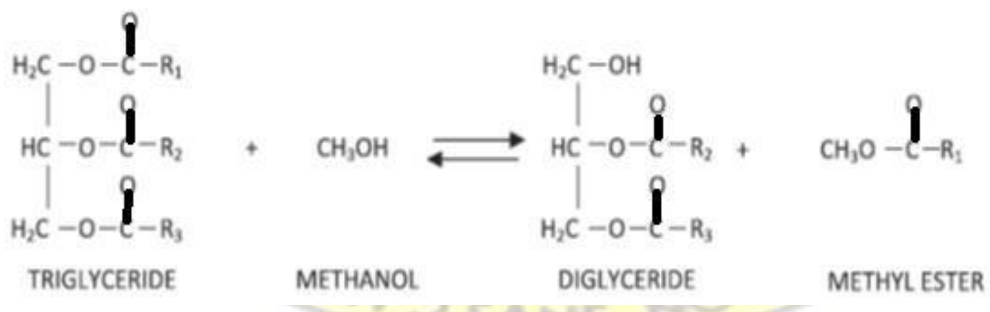
Table 4.4 Kinematic viscosity of biodiesel obtained in literature compared with that obtained in this work

Vegetable oil @ 40^0C (mm^2/s)	Viscosity (this work) 40^oC (mm^2/s)	Viscosity(literature)	References
Palm kernel oil	**3.7**	4.8	[1,2]
Coconut oil	**2.4**	2.7-4.1	[3,4,5,6, 7, 8,9]
Jatropha	**3.1**	3.7-5.8	[10,11,12,13]

[1] (Alamu *et al.*, 2008a)
[2] (Alamu *et al.*, 2007)
[3] (How *et al.*, 2014)
[4] (Habibullah *et al.*, 2014)
[5] (Liaquat *et al.*, 2013)
[6] (Hoekman *et al.*, 2012)
[7] (Nakpong & Wootthikanokkhan, 2010)
[8] (Puhan *et al.*, 2009)
[9] (Alptekin & Canakci, 2008)
[10] (Ganapathy *et al.*, 2011)
[11] (Chauhan, Kumar, Du Jun & Lee, 2010)
[12] (Rao, 2011)
[13] (Jindal *et al.*, 2010)

4.1.3. Influence of Methanol to Oil Ratio on Yield

Ideally, one mole of biodiesel requires 3 moles of alcohol in transesterification.



(4.1)

However, due to the reversible nature of the reaction as in Equation 4.1, excess alcohol is usually used in transesterification in order to shift the reaction to the product side (Leung & Guo, 2006).

The effect of methanol to oil in the range of 4:1 to 8:1 (molar ratio) was analysed. The temperature of the reaction was kept same at 65 ^{O}C, and transesterification was conducted for 1 hour. A fixed concentration of NaOH was used for the reaction. Investigation of the three oils (JCME, PKOME and COME) showed methanol to oil ratio rise results in yield increase till the best yield is arrived at (Figure 4.2).

This is because higher mass ratio of reactants intensifies interaction between the methanol and oil molecules.

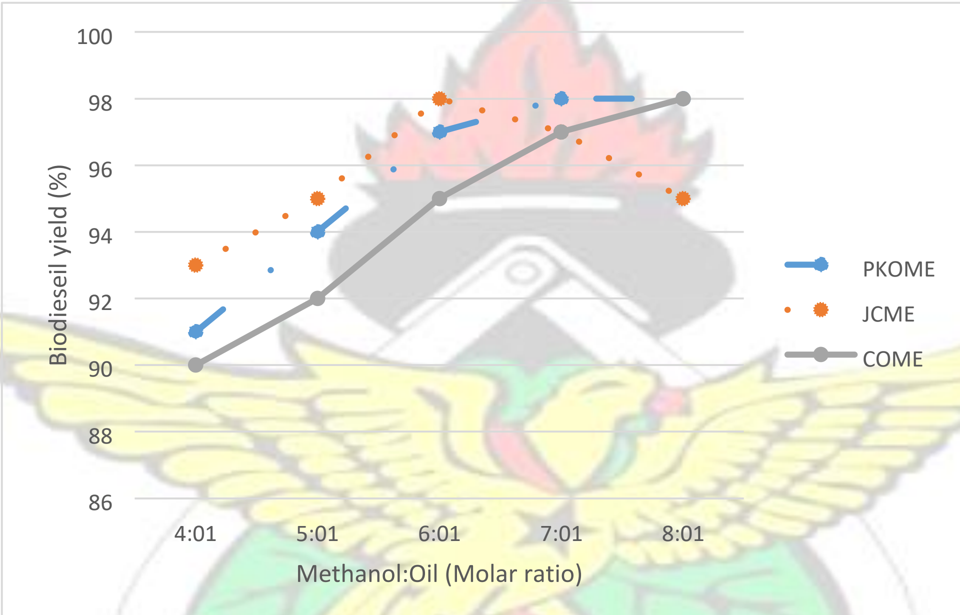


Figure 4.2 Influence of alcohol: oil molar ratio on biodiesel yield

The optimum methanol: oil molar ratio for production of biodiesel from Jatropha curcas methyl ester is 6:1. But it seems that after the optimum yield was reached the yield began to decline for JCME.

Methanol to oil molar ratio of 8:1 were found to be optimum ratios for palm kernel oil and coconut oil biodiesel production yield. The yield obtained for each at this molar ratio was 98%.

4.2.Palm Kernel Oil Biodiesel

Palm kernel oil was acquired from the open market in Koforidua and processed into biodiesel through transesterification process. Their properties are discussed in the next section.

4.2.1. Fuel Properties

Palm kernel oil methyl ester (PKOME) was characterised together with petroleum diesel according to the ASTM D6751 standard as explained in section 3. Table 4.5 shows the properties of PKOME obtained in comparison with petroleum diesel and international standards.

Table 4.5 Fuel properties of PKOME obtained

Properties	PKOME	Petroleum Diesel	ASTM D6751	EN 14214
Kinematic Viscosity @ 40 ^{0} C (mm^2/s)	3.7	2.6	1.9-6	3.5-5
Cetane number	50	49	47 min	51 min
Pour point (^{0} C)	1	1	-15 to 6	-
Cloud point (^{0} C)	6	2	-	-

Flash point (^{0}C)	170	90	93 min	120 min
Higher calorific value (MJ/kg)	44	46	-	35
Acid value (mg KOH/g)	3.4	0.17	0.8 max	0.5 max
Density (kg/m^3)	894	839	880	860-900

4.2.1.1. Kinematic Viscosity

Viscosity of 3.7 mm^2/s PKOME compares very well with petroleum diesel and passes the two major international standards for biodiesel (ASTM D6751 and EN14214). It also compares favourably with those obtained in literature. Alamu et al., (2008b), Jitputti, et al., (2006) and Benjapornkulaphong, et al. (2009) obtained 4.839, 28.65, 28.52 mm^2/s respectively. However this is still slightly higher than petroleum diesel (2.6 mm^2/s) and it is widely reported in literature that methyl esters have higher viscosities relative to Petroleum diesel due to high fatty acid composition (Roy *et al.*, 2013; Knothe & Steidley, 2005). Viscosity is the major reason why transesterification is necessary (Ma & Hanna, 1999). Biodiesel with viscosity above the required standard can cause poor fuel mixing (Haşimoğlu *et al.*, 2008). Fatty acid composition determines the degree of saturation and the higher the composition the higher the degree of saturation. Viscosity increases with increasing degree of saturation.

4.2.1.2. Cloud point

The cloud point of 6^{0}C obtained for PKOME compares very well with petroleum diesel of 2^{0}C. Flow properties such as pour point (PP) and cloud point (CP) are important in determining performance of fuel flow system. Viscosity is known to be influenced strongly by temperature and is inversely proportional to temperature. Operating a diesel engine at low temperatures especially in cold climate regions can be difficult because of high viscosities. This is why low temperature properties are necessary to determine feasibility of use in cold countries. The temperature at which cloud wax crystals first appear in the oil when it is cooled is termed cloud point. This is usually visible to the naked eye.

4.2.1.3. Pour point

Pour point of 1^0C was obtained for PKOME. Petroleum diesel also has the same pour point of 1^0C. This implies that the lowest temperature at which both palm kernel oil biodiesel (obtained in this work) and petroleum diesel can be poured is the same. Alamu et al. (2008a) obtained pour point of PKOME as 2^0C. There are no EN standards for pour point but the ASTM standard range is -15 to 6. Pour point of PKOME measure thus meets both standards.

4.2.1.4. Flash point

Flash point for PKOME obtained was 170 ^{0}C compared with 167 ^{0}C obtained by Alamu, et al. (2008b). The ASTM D6751 standard requires the minimum flash point to be 93^0C while the minimum for EN 14214 standard is 120 ^{0}C.

Flash point specification ensures that the biodiesel produced has been purified enough by the elimination of extra alcohol. The higher the excess content of alcohol in the biodiesel the lower the flash point will be.

4.2.1.5. Calorific value

At 44 MJ/kg palm kernel oil biodiesel is close to petroleum diesel (46M J/kg) and meets the standards. Alamu et al. (2008a) obtained 40 MJ/kg as calorific value for PKOME.

Calorific value also lower/upper heating values can be used to distinguish among different fuels their likelihood to produce more or less power or torque per the same volume. It compares the energy content per litre for the various fuels under consideration.

4.2.1.6. Acid value

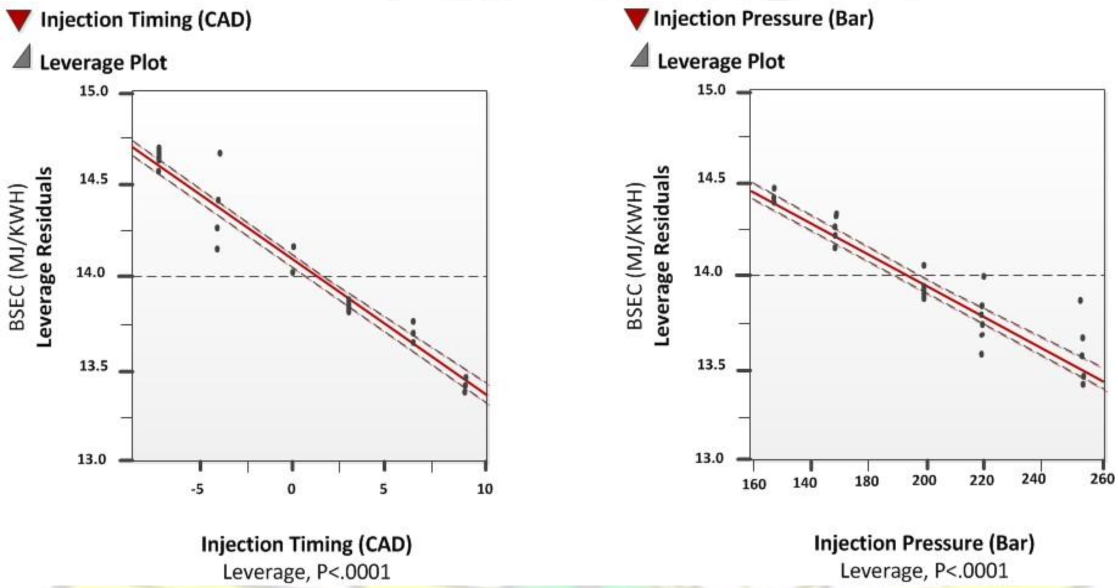
The acid value for PKOME is 3.4 mg KOH/g, which is higher than petroleum diesel at 0.17 mg KOH/g. Thus, PKOME fails the required standard maximum limits for both ASTM and EN of 0.5 mg KOH/g. It is an indication that PKOME is more unstable compared with petroleum diesel. Acid value is a measure of auto-oxidation, storage stability or metal contamination (Jakeria, Fazal & Haseeb, 2014).

4.2.1.7.Density

The results show the Density of PKOME of 894 kg/m^3 exceeds that of petroleum diesel of 839kg/m^3 but well within the standards of EN (860-900 kg/m^3). It has been generally reported that biodiesel has a higher density than petroleum diesel. This is why biodiesel is considered already ‘chemically advanced’ in terms of injection timing (Caresana, 2011).

4.2.2. Influence of Injection Timing and Pressure on PKOME Engine

From Figure 4.3a, the result of BSEC verses Injection timing shows that injection advance lowers the fuel consumption while a retardation increases fuel consumption for an engine fuelled with PKOME.



(a) (b)

Figure 4.3, JMP 10 BSEC leverage plots for (a) Injection timing (b) Injection pressure

For a PKOME fuelled engine the p-value (0.0001*) in Table 4.6 portrays there is a substantial influence of pressure of injection on BSEC. Figure 4.3 (b) indicates that the higher the injection pressure the lower the fuel consumption. BSEC for PKOME decreased all the way from 14.4 MJ/kW-h to 13.6 MJ/kW-h at 150 and 250 bar respectively. Higher pressures are associated with high temperatures which led to near complete combustion but with adverse effect on NOx.

Table 4.6 shows parameter estimates obtained from JMP DOE analysis for BSEC. It is noticed that the combined result of timing and pressure had a p-value of 0.2146. This implies the combined effect of both parameters on BSEC of PKOME is not significant.

Table 4.6 Parameter estimates for injection timing & pressure influence on PKOME

Term	Estimate	Std Error	t Ratio	Prob>t
Injection timing (CAD)	-0.08	0.003812	-20.99	<0.0001*
Injection pressure (Bar)	-0.007733	0.000552	-14.00	<0.0001*
Injection timing*Injection pressure (Bar)	0.0001371	0.000108	1.27	0.2146

From Figure 4.4, it is worth noting that advancing injection timing reduces CO formation for PKOME fuelled engine while retardation however increases CO formation. This is the reverse compared with petroleum diesel engine combustion where injection advance is rather accompanied with increase CO formation (Hillion, Buhlbuck, Chauvin & Petit, 2009). Injection retard means fuel is injected somewhat later than it normally should while injection advance means the fuel is injected earlier. Where there is retard there is not enough time for fuel to atomize and form a homogeneous mixture for complete combustion.

Injection timing therefore requires modification for use of PKOME if less CO formation is expected. Similarly, increased injection pressure resulted in less CO formation. High injection pressures result in good fuel atomization and hence complete combustion.

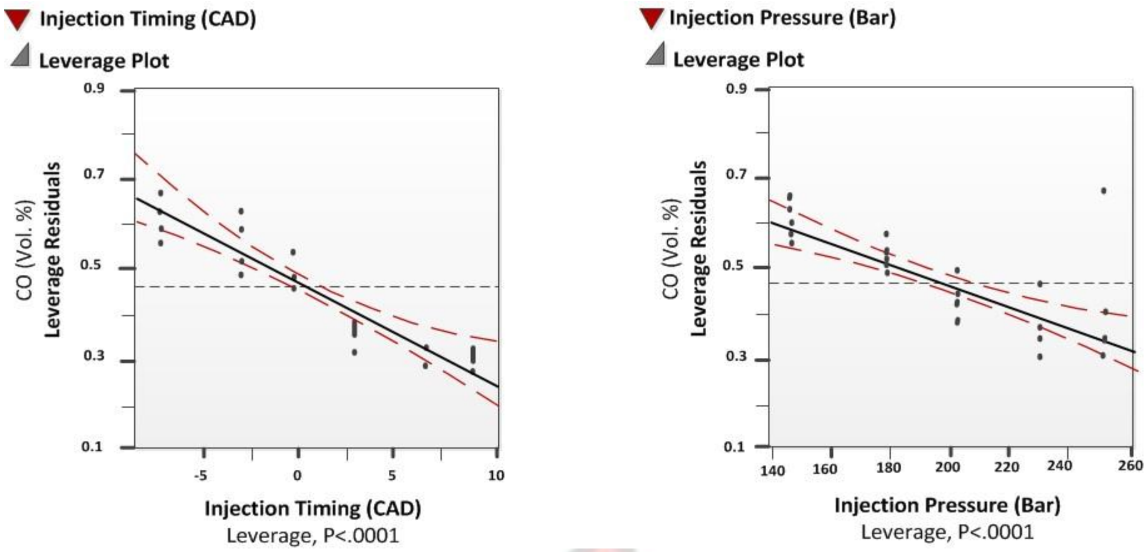


Figure 4.4, JMP 10 CO leverage plots for (a) Injection timing (b) Injection pressure

The parameter estimates below (Table 4.7) show that though individual engine components of injection timing and pressure had significant influence on CO formation their combined effect (0.2617) was not significant.

Table 4.7 Parameter estimates for injection timing & pressure influence on PKOME, CO formation

Term	Estimate	Std Error	t Ratio	Prob>t
Injection timing (CAD)	-0.02301	0.002524	-9.12	<0.0001*
Injection pressure (Bar)	-0.002287	0.000366	-6.25	<0.0001*
Injection timing*Injection pressure (Bar)	0.0000819	07.139	1.15	0.2617

HC formation is usually accompanied by CO formation. The graph in Figure 4.5 shows that retardation favours HC formation while for the same reason as CO, high low injections pressures also favour HC formation.

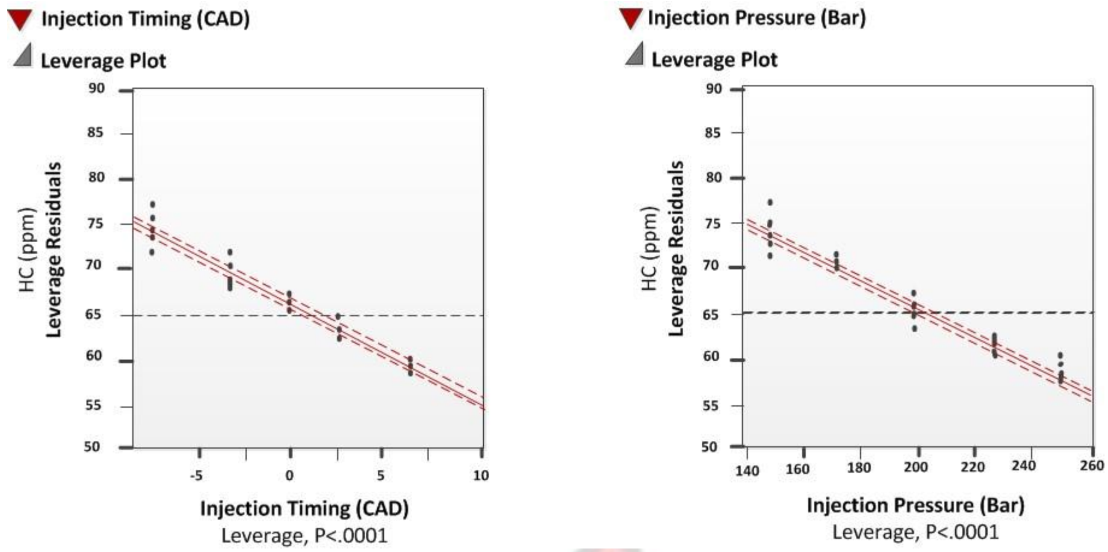


Figure 4.5 JMP 10 HC leverage plots for (a) Injection timing (b) Injection pressure

However, the parameter estimates (Table 4.8) depict that the collective effect of timing and pressure of injection have significant influence on HC formation. Thus for a PKOME fuelled engine, to control HC formation will require adjusting both injection timing and injection pressure parameters.

Table 4.8 parameter estimates for PKOME, HC formation

Term	Estimate	Std Error	t Ratio	Prob>t
Injection timing (CAD)	-1.173333	0.0065614	-17.88	<0.0001*
Injection pressure (Bar)	-0.168	0.009508	-17.67	<0.0001*
Injection timing*Injection pressure (Bar)	0.0109714	0.001856	5.91	<0.0001*

Oxides of Nitrogen increased linearly with injection advanced but reduced with retardation (Figure 4.6). Generally, NOx formation is higher for biodiesel fuels than for petroleum diesel because of the excess oxygen. It is generally known that NOx emissions occur at high temperatures (Pulkrabek, 1997). It is also seen that the higher the pressures the higher the NOx formation since higher pressures lead to higher temperatures. It is now well noted that an effort to reduce fuel consumption, CO, HC and NOx formation will result in increasing NOx formation and vice versa.

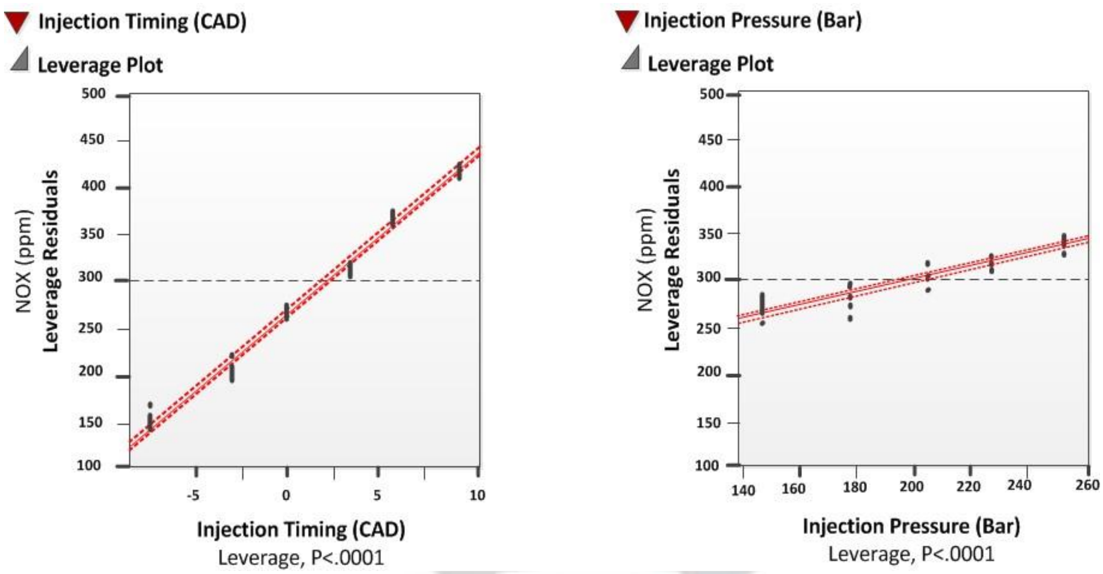


Figure 4.6 JMP 10 NOx leverage plots for (a) Injection timing (b) Injection pressure

4.2.3. Desirability approach

The desirability method is a very widely used method in industry for optimization involving many responses. Desirability is given as

$D=(d_1(Y_1)d_2(Y_2)\ldots d_k(Y_k))^{1/k}$ where **k** represents quantity of responses. In this work, full factorial method was used for the optimization of injection parameters such as injection timing and pressure for recorded properties of brakes specific energy consumption, carbon monoxide, hydrocarbon and oxides of nitrogen with the help of Design Expert software (Table 4.9).

Table 4.9 Maximum desirability points for PKOME engine parameters validated

Injection timing(CAD)	Injection pressure(Bar)	BSEC (MJ/kW-h)	CO (ppm)	HC (Vol. %)	NOX (ppm)	Desirability
3	**250**	**13.4**	**0.27**	**56**	**340**	**0.726**
3	225	13.6	0.29	58	330	0.699
0	250	13.6	0.38	58	300	0.698
-3	225	13.9	0.47	63	223	0.652
0	225	13.8	0.41	61	292	0.651
3	200	13.8	0.38	65	308	0.626
-6	250	14.2	0.49	64	179	0.611

These results were validated and agreed mostly with measured engine runs in the laboratory with an error of 0.005%. The maximum desirability was 72.6% at injection pressure of 250bar and injection advance of 3^0. However, at this desirability CO, HC and fuel consumption were at their minimum at the expense of high NOx emissions (340 ppm). If NOx reduction is the goal, then the best parameter will be at 250 bar injection pressure and injection retard of 6^0.

4.3.Coconut Oil Biodiesel

Coconut oil methyl ester (COME) was produced from coconut oil obtained from Koforidua market. COME was characterised and compared with petroleum diesel according to the ASTM D6751 standard as explained in section 3. Table 4.10 shows the properties of COME obtained in comparison with petroleum diesel and international standards. This compares well with published data (Khang *et al.*, 2014; Atabani *et al.*, 2013; Liaquat *et al.*, 2013; Kumar *et al.*, 2010; Nakpong & Wootthikanokkhan, 2010).

4.3.1. Fuel Properties

4.3.1.1.Kinematic viscosity

It can be seen from the Table 4.10, that coconut oil biodiesel possesses the lowest kinematic viscosity compared with diesel and falls well within the required ASTM standard. Kinematic viscosity of coconut oil dropped from 27 mm^2/s to 2.4 mm^2/s after transesterification. The kinematic viscosity of COME (2.4 mm^2/s) was found to be lower than petroleum diesel (2.6 mm^2/s).

Table 4.10 fuel properties of COME obtained

Properties	COME	Petroleum Diesel	ASTM D6751	EN 14214
Kinematic Viscosity @ 40^0C (mm^2/s)	2.4	2.6	1.9-6	3.5-5
Cetane number	55	49	47min	51min
Pour point (^0C)	-5	1	-15 to 6	-
Cloud point (^0C)	2	2	-	-
Flash point (^0C)	122	90	93min	120min
High calorific value (MJ/kg)	42	46	-	35
Acid value (mg KOH/g)	2	0.17	0.5 max	0.5 max
Density (kg/m^3)	878	839	880	860-900

This met the ASTM D6751 standard (1.9-6 mm^2/s) and the EN 14214 standard (3.5-5 mm^2/s). Some authours obtained kinematic viscosity of 3.1435 and 2.8550 respectively (Fattah, Masjuki, Kalam, Wakil, Rashedul & Abedin, 2014)

4.3.1.2.Cetane number

Cetane number of 55 was obtained for COME and that of petroleum diesel was 49. The minimum cetane number required by ASTM and EN standards are 47 and 51, respectively. Since a shorter ignition delay (ID) corresponds to a higher CN and vice versa it implies this COME will ignite at a lower temperature than petroleum diesel. Cetane number obtained for COME fell well within the standards and was much better than petroleum diesel.

4.3.1.3.Cloud point

The cloud point obtained for COME (2 ^{0}C) compares very well with petroleum diesel (2^{0}C) though there are no specified limits prescribed for both ASTM and EN standards. Operating a diesel engine at low temperatures especially in cold climate regions can be difficult because of high viscosities. This is why low temperature properties are necessary to determine feasibility of use in cold countries. The temperature at which cloud wax crystals first appear in the oil when it is cooled is termed cloud point. This is usually visible to the naked eye.

4.3.1.4.Pour point

Pour point of COME (-5 ^{0}C) measured is better than petroleum diesel and PKOME (1^{0}C) and thus giving COME better flow properties. Thus at -5 ^{0}C it will still be possible to pour COME.

4.3.1.5.Flash point

Flash point of COME obtained was 122 ^{0}C and fell well within both standards. The ASTM D6751 standard requires the minimum flash point to be 93^{0}C while the minimum for EN 14214 standard is 120 ^{0}C. Flash point specification ensures that the biodiesel produced has been sufficiently purified by the removal of excess alcohol (methanol or ethanol). The higher the excess content of alcohol in the biodiesel the lower the flash point will be.

4.3.1.6.Calorific value

Calorific value of coconut oil biodiesel obtained is 42 MJ/kg while petroleum diesel measured 46 MJ/kg. There is no minimum ASTM standard for biodiesel however the results obtained meets the EN minimum standard of 35 MJ/kg.

4.3.1.7.Acid value

The acid value for COME is 3.4 mg KOH/g and is higher than petroleum diesel which recorded 0.17 mg KOH/g. The required standard limits for both ASTM and EN is 0.5 mg KOH/g. coconut oil biodiesel thus did not meet the required biodiesel standard for acid value. However, it is an indication that biodiesel in general is more unstable compared with petroleum diesel (Schober & Mittelbach, 2005). Acid value is a measure of auto-oxidation, storage stability or mental contamination (Jakeria *et al.*, 2014). Instability of biodiesel in general terms refers to change of the fuel composition and properties as a result degradation. When the biodiesel produced is tested on the first day its properties differ from when it is tested after a number of days since it degrades.

4.3.1.8.Density

The results show the density of COME is 878 kg/m^3 exceeds that of petroleum diesel of 839 kg/m^3. This meets bot the ASTM standard of 880 kg/m^3 and EN standard of 860-900 kg/m^3. Density of the biodiesel was higher than petroleum diesel which is convenient since the higher speed will make up for the low calorific value.

4.3.2. Influence of Injection Timing and Pressure on COME Fuelled Engine

Fuel consumption and emission analysis were investigated for COME as for PKOME. Appendix B shows the full factorial results obtained. The results obtained for CO emissions were not different from PKOME except the p-value showed that both parameters did not influence the emissions significantly.

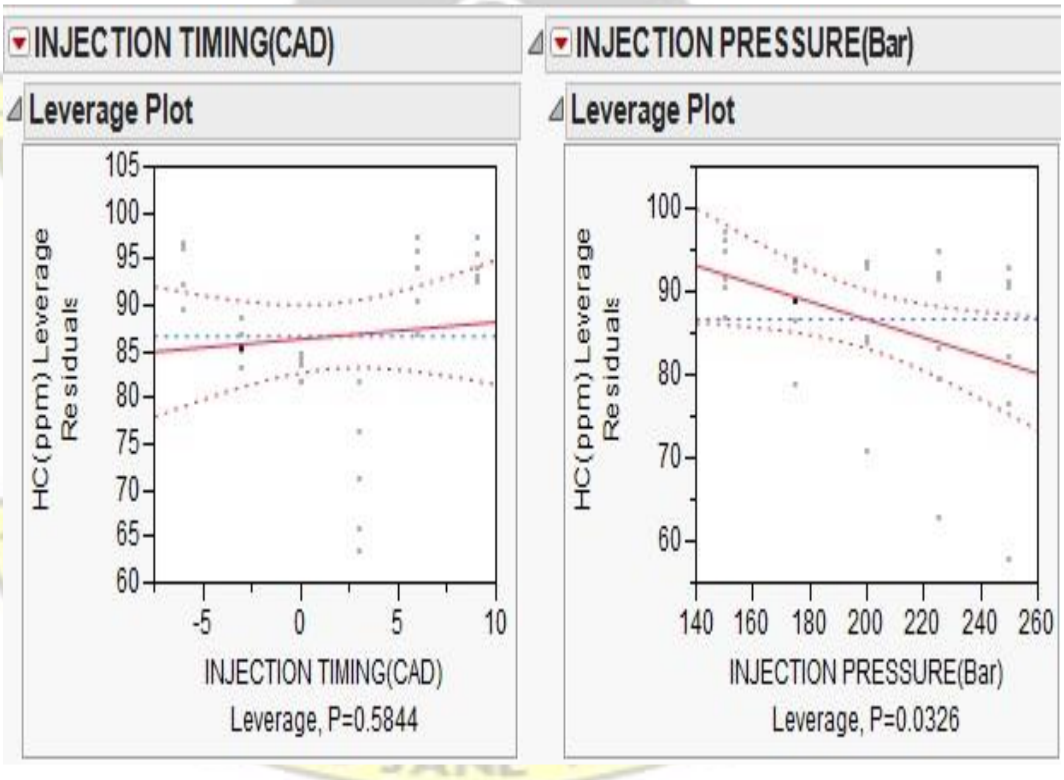


Figure 4.7 JMP 10 COME leverage plots for (a) Injection timing (b) Injection pressure, HC emissions

Injection timing parameter did not have significant impact on COME engine emissions since the p-value of 0.5844 was far above the primary value of 0.05 that shows significance. Just like PKOME, while injection pressure increased, HC emissions reduced (Figure 4.7). The combined effect of injection timing and injection pressure was significant in HC emissions for COME. The results for BSEC though followed the same trend as PKOME showed a high significance with a p-value of 0.0014.

4.3.3. Desirability approach

Maximum desirability points were obtained (Table 4.11) which were validated through engine runs with error 0.05%. Engine parameters chosen for COME fuelled engine for low fuel consumption and emissions are injection pressure of 250 Bar and timing advance of 3^0 as with a high desirability of 82%.

Table 4.11 fuel consumption and engine emissions data obtained for COME

Injection timing(CAD)	Injection pressure(Bar)	BSEC (MJ/kW-h)	CO (ppm)	HC (Vol. %)	NOX (ppm)	Desirability
3	**250**	**13.8**	**0.24**	**74**	**176**	**0.82**
0	250	14.2	0.3	75	142	0.59
6	225	14.1	0.26	78	167	0.577
-3	225	14.4	0.31	79	135	0.55

At these points minimum BSEC (13.8MJ/kW-h), CO (0.24ppm), HC (74Vol. %) at the expense of high emissions of NOx (176 ppm) are expected. For lower NOx emissions at the expense of other parameters, then injection retardation of 3^0 and injection pressure of 225 bar are the optimum parameters for COME engine.

4.4. Jatropha Oil Biodiesel

Jatropha oil was obtained from the Northern region of Ghana processed into biodiesel through transesterification process. Their properties are discussed in the next section.

4.4.1. Fuel Properties

Table 4.12 shows the properties of JCME obtained in comparison with petroleum diesel and international standards. The properties obtained are close to petroleum diesel and meets international biodiesel standards.

Table 4.12 JCME optimised properties compared to petroleum diesel

Properties	JCME	Petroleum Diesel	ASTM D6751	EN 14214
Kinematic Viscosity @ 40^0C (mm^2/s)	3.1	2.6	1.9-6	3.5-5
Cetane number	52	49	47 min	51 min
Pour point (^{0}C)	-9	1	-15 to 6	-
Cloud point (^{0}C)	-6	2	-	-
Flash point (^{0}C)	175	90	93 min	120 min
High calorific value (MJ/kg)	42	46	-	35
Acid value (mg KOH/g)	2	0.17	0.5 max	0.5 max
Density (kg/m^3)	898	839	880	860-900

4.4.1.1.Kinematic viscosity

It can be seen from the Table 4.12, that the kinematic viscosity of JCME (3.1 mm^2/s) was found to be lower than petroleum diesel (2.6 mm^2/s). Though this met the ASTM D6751 standard (1.9-6 mm^2/s) it failed the EN 14214 standard (3.5-5 mm^2/s). Kinematic viscosity is the most important fuel property as it determines whether a fuel is a viable alternative or not. It affects operation of fuel injection components such as fuel pumps and nozzles.

4.4.1.2.Cetane number

Cetane number of 52 was obtained for JCME and that of petroleum diesel was 49. Cetane number obtained for JCME fell well within the standards and was much better than petroleum diesel. The minimum cetane number required by ASTM and EN standards are 47 and 51 respectively.

4.4.1.3.Cloud point

The cloud point result obtained for JCME is -6^{0}C and compares very well with petroleum diesel cloud point of 2^{0}C obtained. Though, there are no specified limits prescribed for both ASTM and EN standards.

Operating a diesel engine at low temperatures especially in cold climate regions can be difficult because of high viscosities. This is why low temperature properties are necessary to determine feasibility of use in cold countries. The temperature at which cloud wax crystals first appear in the oil when it is cooled is termed cloud point. This is usually visible to the naked eye.

4.4.1.4.Pour point

Pour point of JCME (-9 ^{0}C) measured is better than petroleum diesel and PKOME (1^{0}C) and COME (-5 ^{0}C) and thus giving COME better flow properties. Thus at -9 ^{0}C it will still be possible to pour COME.

4.4.1.5.Flash point

Flash point of JCME obtained was 175 ^{0}C and fell well within both standards. The ASTM D6751 standard requires the minimum flash point to be 93^{0}C while the minimum for EN 14214 standard is 120 ^{0}C. Flash point specification ensures that the biodiesel produced has been sufficiently purified by the removal of excess alcohol (methanol or ethanol). The higher the excess content of alcohol in the biodiesel the lower the flash point will be.

4.4.1.6.Calorific value

Higher calorific value of petroleum diesel obtained is 46 MJ/kg and that recorded for JCME is 42 MJ/kg. There is no minimum ASTM standard for biodiesel however the results obtained meets the EN minimum standard of 35 MJ/kg.

4.4.1.7.Acid value

The acid value of 2 mg KOH/g was recorded for JCME. This is higher than petroleum diesel acid value of 0.17 mg KOH/g recorded. Thus JCME fails the required standard limits for both ASTM and EN (0.5 mg KOH/g, max). Acid value is a measure of autooxidation, storage stability or mental contamination (Jakeria, et al. 2014). However, it is an indication that biodiesel in general is more unstable compared with petroleum diesel (Schober & Mittelbach, 2005). Instability of biodiesel in general terms refers to change of the fuel composition and properties as a result degradation. When the biodiesel produced is tested on the first day its properties differ from when it is tested after a number of days since it degrades.

4.4.1.8.Density

Density of the biodiesel was higher than petroleum diesel which is convenient since the higher speed will make up for the low calorific value. The results show the Density of JCME of 898 kg/m^3 exceeds that of petroleum diesel of 839kg/m^3 but well within the standard of EN of 860-900 kg/m^3.

4.4.2. Influence of Injection Timing and Pressure on JCME fuelled engine

Fuel consumption and emissions measurements were taken at according to the experimental matrix. Appendix C shows the full factorial results obtained. The pvalues from Table 4.13 indicate that the influence of injection timing on brake specific energy consumption for Jatropha biodiesel was not significant since the p-value of 0.0456 was far short of the significant value. The most significant parameter was injection pressure with a p-value of 0.0072. Thus, for a Jatropha fuelled engine, injection pressure needs to be optimised to obtain optimum fuel consumption.

Table 4.13 parameter estimates for JCME for BSEC

Term	Estimate	Std Error	t Ratio	Prob>t
Injection timing (CAD)	-1.173333	0.0065614	-17.88	0.0456
Injection pressure (Bar)	-0.168	0.009508	-17.67	0.0072*
Injection timing*Injection pressure (Bar)	0.0109714	0.001856	5.91	0.8773

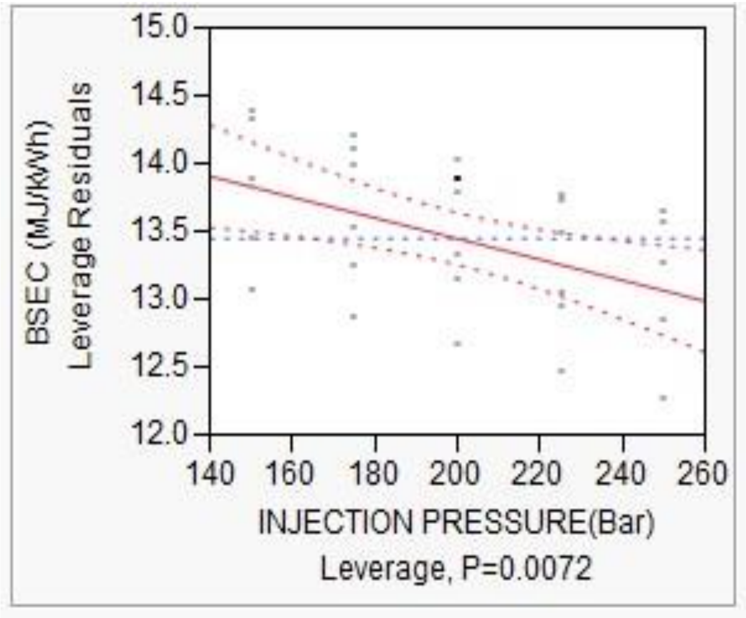


Figure 4.8 Brake specific energy consumption variation with injection pressure increase

It is noticed from Figure 4.8 that for Jatropha curcas methyl ester, there is constant reduction in fuel consumption as the pressure of injection is increased beginning 150 Bar to 250 Bar. The higher the injection pressure the better the chance of homogeneity in the combustion chamber and the lesser fuel is wasted. Higher pressures lead to higher temperatures enhancing combustion.

Carbon monoxide emissions reduced continuously with injection advance and vice versa (Figure 4.9).

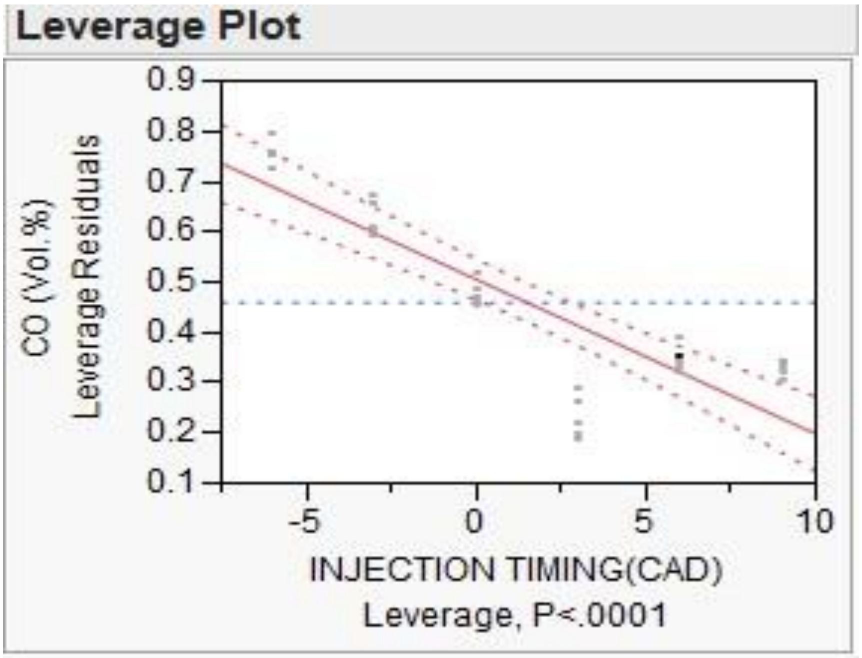


Figure 4.9 Carbon monoxide emission trend with varying injection timing

The p-value ($p<0.0001$) also proves that injection timing is very influential on carbon monoxide emissions of Jatropha fuelled engine. As shown in Figure 4.10 the higher the pressure the lower the carbon monoxide formation.

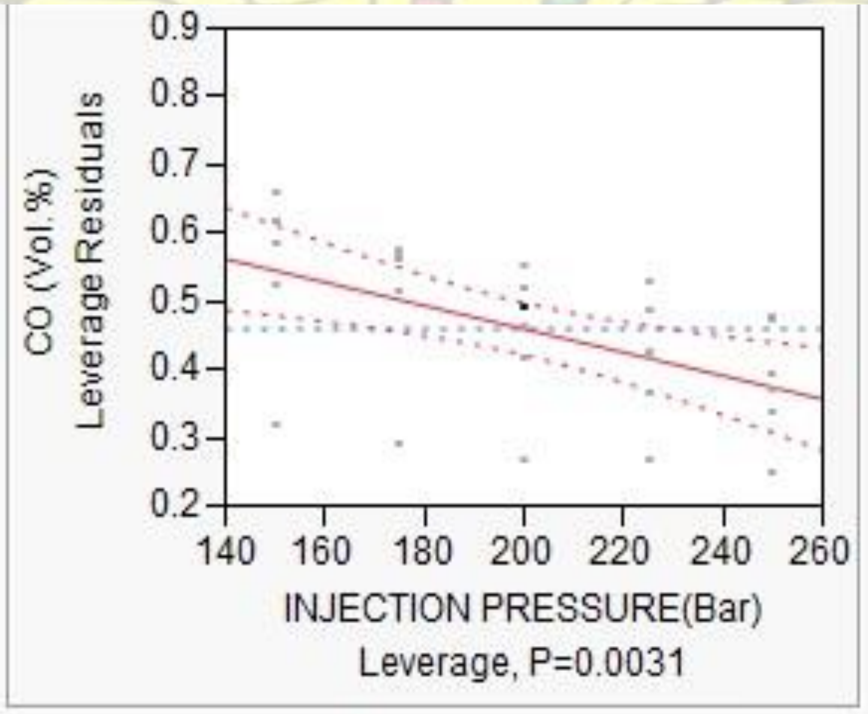


Figure 4.10 carbon monoxide emissions with varying injection pressures

Higher pressures lead to higher temperatures which contributes to a more complete combustion hence the less CO formation.

With a p-value of 0.5159 the effect of injection timing on hydrocarbon formation was not significant. The effect of injection pressure on HC formation was however very significant with a p-value less than 0.0001. Hydrocarbon formation lessened continuously as injection pressure increased. The high oxygen presence in Jatropha biodiesel coupled with its associated high temperatures ensures a more complete combustion leading to less hydrocarbon formation. The combined effect of Injection timing and pressure for a Jatropha biodiesel fuelled engine was found not to be significant with a p-value of 0.9208.

Figure 4.11 shows that when the injection timing is advanced, the NOx emissions increase significantly. Firstly, NOx formation is high in cases of high temperatures and pressures. The ballast oxygen contained in Jatropha biodiesel causes high temperatures in the combustion chamber leading to high tendencies of NOx formation. Secondly advancing injection timing means less time for fuel to be properly atomised before combustion. This it creates uneven temperature distribution leading to high pressures.

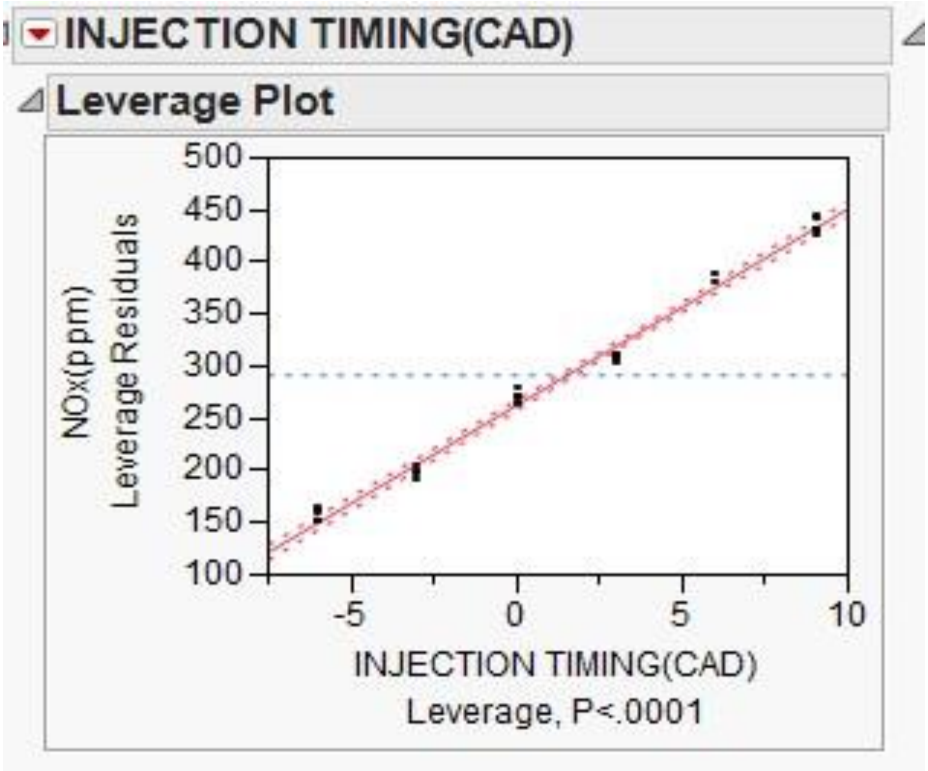


Figure 4.11 NOx emissions with varying injection timings

The effect of injection pressure on NOx formation was also found to be very significant as the p-value was found to be 0.0001 (Figure 4.12)

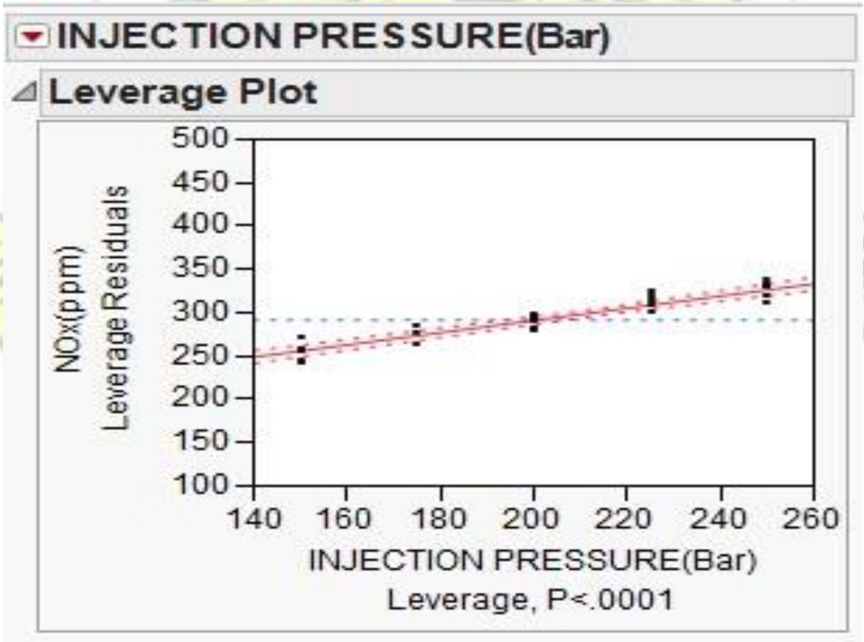


Figure 4.12 NOx emissions with varying injection pressures

4.4.3. Desirability points for Jatropha

Full factorial method was chosen for the optimization process for injection timing and pressure for results of BSEC, CO, HC and NOx with the help of Design Expert software (Table 4.14). The results are the validated engine values.

Table 4.14 Maximum desirability points for JCME engine parameters validated

Injection timing(CAD)	**Injection pressure(Bar)**	**BSEC (MJ/kW-h)**	**CO (ppm)**	**HC (Vol. %)**	**NOX (ppm)**	**Desirability**
3	**200**	**12.6**	**0.22**	**60**	**310**	**0.763**
-3	225	13.2	0.56	65	220	0.587

The maximum desirability was 76.3% at injection pressure of 200 bar and injection advance of 3^0. However, at this desirability CO, HC and fuel consumption were at their minimum at the expense of high NOx emissions (310 ppm). If NOx reduction is the goal, then the best parameter will be at 225 bar injection pressure and injection retard of 3^0.

4.5. Comparison of Biodiesel and Petroleum Diesel Emissions and Fuel Consumption

The chosen desired optimized parameters and responses for PKOME, JCME, COME and petroleum diesel are compared in Figure 4.13.

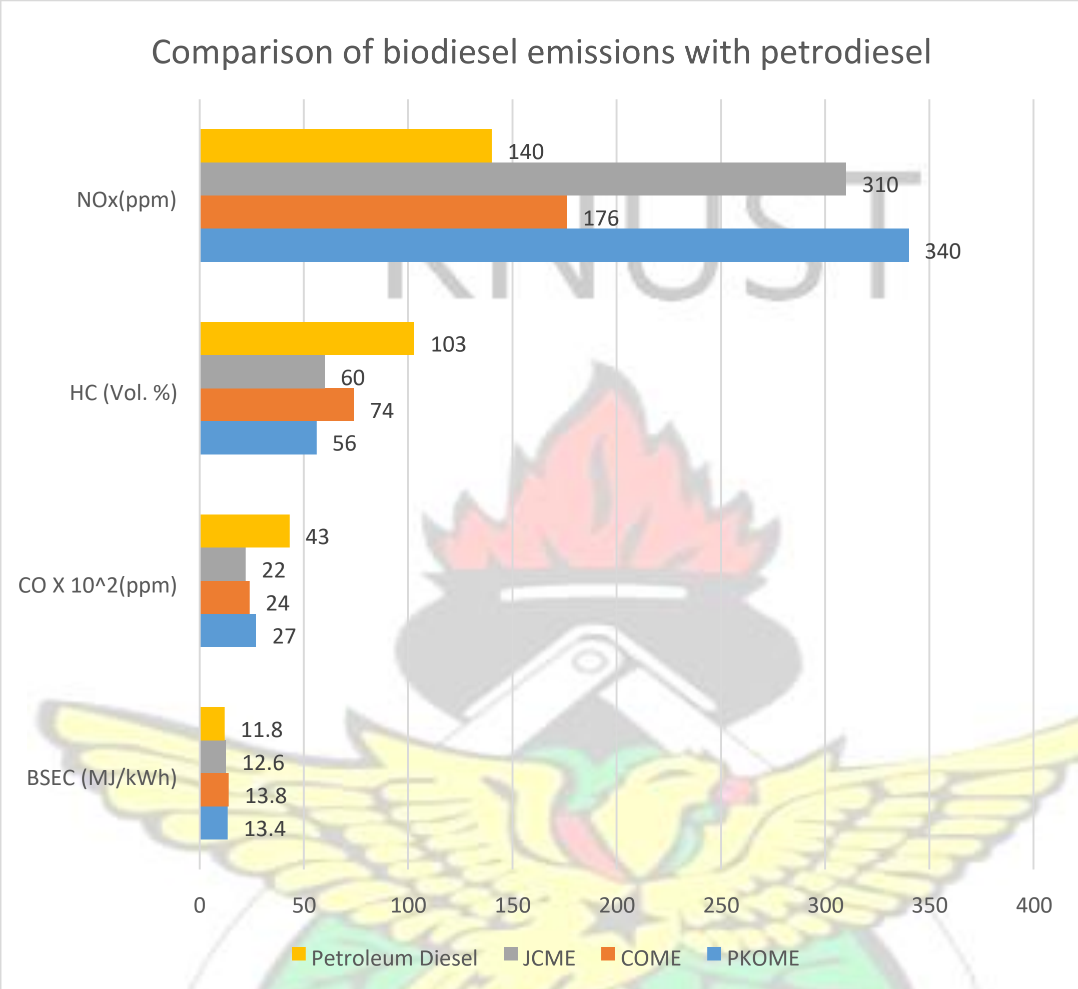


Figure 4.13 Comparing optimised COME, PKOME and JCME engine performance results with petroleum diesel

Brake specific energy consumption of petroleum diesel was better than COME and PKOME fuelled engine by approximately 14 % but much closer to Jatropha biodiesel with a difference of only 0.8 MJ/kW-h. This is so since petroleum diesel has a higher calorific value than biodiesel. Pullen & Saeed (2014), stated that energy content is determined by the amount of HC bonds present while petroleum diesel has more of this, biodiesel has more oxygen instead (about 10% more) (Pullen & Saeed, 2014). PKOME fuelled engine fuel consumption is better than COME by about 3%. Carbon monoxide emissions of biodiesel is about 44% less than petroleum diesel engine as seen from the figure 4.13. The excess oxygen in biodiesel present more opportunities for complete combustion hence the lesser carbon monoxide emissions. COME fuelled engine at optimized parameters had lesser (11% less) CO emissions compared to PKOME. Petroleum diesel from the graph is seen to have more HC emissions (46% more) than PKOME. While COME fuelled engine HC emissions were 32% more than that of PKOME. High NOx emissions have always been recorded in published works for biodiesel due to excess oxygen causing high temperatures and hence NOx. After optimisation Petroleum diesel had 20% less NOx than COME fuelled engine and about 60% less than PKOME fuelled engine. Clearly biodiesel usage is at the expense of NOx emissions however biodiesel-biodiesel blending and EGR ratio optimisation can reduce NOx emissions.

4.6. Biodiesel-Biodiesel Blends

Palm kernel oil biodiesel and coconut oil biodiesel were blended in proportions of 100%, 75%, 50%, 25% and 0% to determine optimum physiochemical properties and engine performance. Fuel properties of cetane number, calorific value, density and viscosity was measured for each of the blends.

4.6.1. Effects of PKOME-COME Blends on Properties

The results obtained from the blends of PKOME and COME at different percentages are presented in Table 4.15.

Table 4.15 physiochemical properties of PKOME-COME blends

Run	Component1 A: COME (%)	Component2 B: PKOME (%)	Response1 Calorific Value (MJ/kg)	Response2 Viscosity (Cst)	Response3 Density (kg/m^3)	Response 4 Cetane Number
1	0.00	100.00	44	3.7	894	50
2	25.00	75.00	43.5	3.3	890	51
3	75.00	25.00	42.8	2.8	881	54
5	50.00	50.00	43.2	3	886	52
6	100.00	0.00	42	2.4	878	55

4.6.1.1.Viscosity variation with blend

Viscosity of the PKOME-COME component mix improved as COME percentage increased in the mixture. The following equation was developed from figure 4.14 to predict viscosity of any PKOME-COME blend

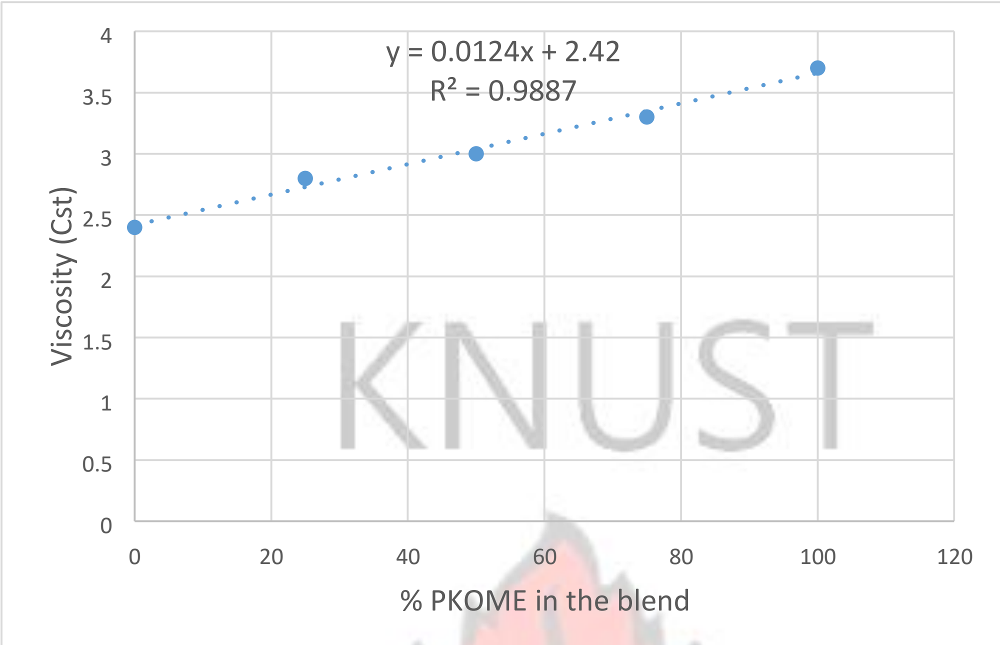


Figure 4.14 Viscosity of PKOME-COME blends

Viscosity (PKOME-COME) = 0.0108x + 2.54 (4.2)

$0 \leq x \geq 100$ (x = % PKOME)

(R^2 = 0.9746)

Since the gradient between Viscosity and percentage of PKOME in the blend is 0.0108 it means for every 1% increase of PKOME, the viscosity of the blend will increase by 0.0108 Cst. This is because the sample of COME used originally had a low viscosity. Best blend for optimum viscosity was 25% PKOME and 75% COME at approximately 2.8Cst (or mm^2/s) comparable to petroleum diesel viscosity of 3.2Cst

4.6.1.2.Calorific value of blend

Calorific values can be used to distinguish among different fuels their likelihood to produce more or less power or torque per the same volume. It compares the energy content per litre for the various fuels under consideration.

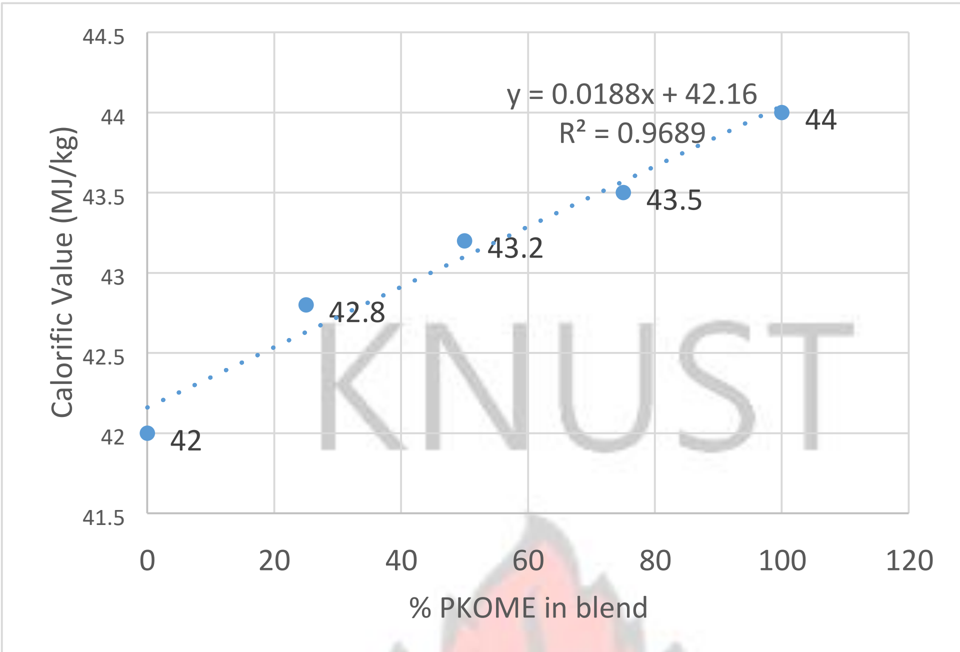


Figure 4.15 Calorific value of PKOME-COME blends

Effect of blending PKOME with COME on calorific value has been studied. The results showed that increasing PKOME percentage increases the calorific value in the blend. The following equation has been developed from figure 4.15 to predict the calorific value of any PKOME-COME blend as follows

Calorific Value (PKOME-COME) = 0.00388x + 42.16 (4.3)

$0 \leq x \geq 100$ (x=% PKOME)

(R^2 = 0.9689)

From the equation it can be seen that for every 1% increase in the PKOME percentage the calorific value of the PKOME-COME blend will increase by 0.00388 MJ/Kg. Coconut oil biodiesel has the lowest heating value at 42 MJ/kg but a blend with 75% PKOME increased the value to 44.3 MJ/kg. Biodiesel has generally been reported to have lesser heating value (Singh & Singh, 2010).This is because for biodiesel, hydrogen and carbon are the key energy sources while oxygen is ballast and has no contribution to thermal energy. A mixture of various hydrocarbon molecules and other elements such as oxygen make up petrodiesel. Hence due to its high oxygen content, biodiesel has lower heating values than petroleum diesel (Hoekman *et al.*, 2012).

4.6.1.3.Cetane number variation with blend

Cetane number (CN) is used to determine the fuel quality used in Compression Ignition (CI) engines. It is dimensionless and related to ignition delay (ID) time, the time that passes between injection of the fuel and start of ignition.

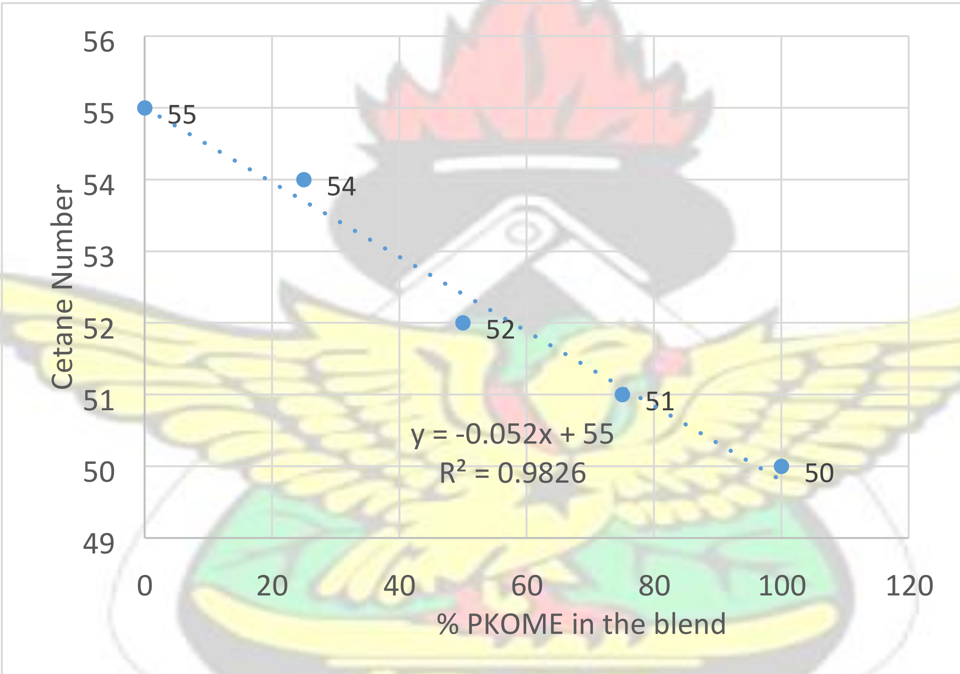


Figure 4.16 Cetane number of PKOME-COME blends

It is noticed from Figure 4.16, that the biodiesel with the closest CN to petroleum diesel (CN=49) is PKOME (CN=48). It is also seen that COME had the more favourable CN of 55 and the best blend for improved CN is 25% PKOME and 75% COME at CN of 54. An equation was developed from figure 4.16 to predict Cetane number of any PKOME-COME blend. From equation 4.3, For every 1% increase of PKOME in the blend, the cetane number will reduce by 0.052.

Cetane Number (PKOME-COME) = -0.052x + 55 (4.4)

$0 \leq x \geq 100$ (x = % PKOME)

$(R^2 = 0.9826)$

4.6.1.4.Density variation with blend

The air to fuel ratio and energy consumpton within the combustion chamber are affected largely by the fuel density. Biodiesel fuel density is very much affected by degree of unsaturation where the higher the unsaturation the denser the fuel.

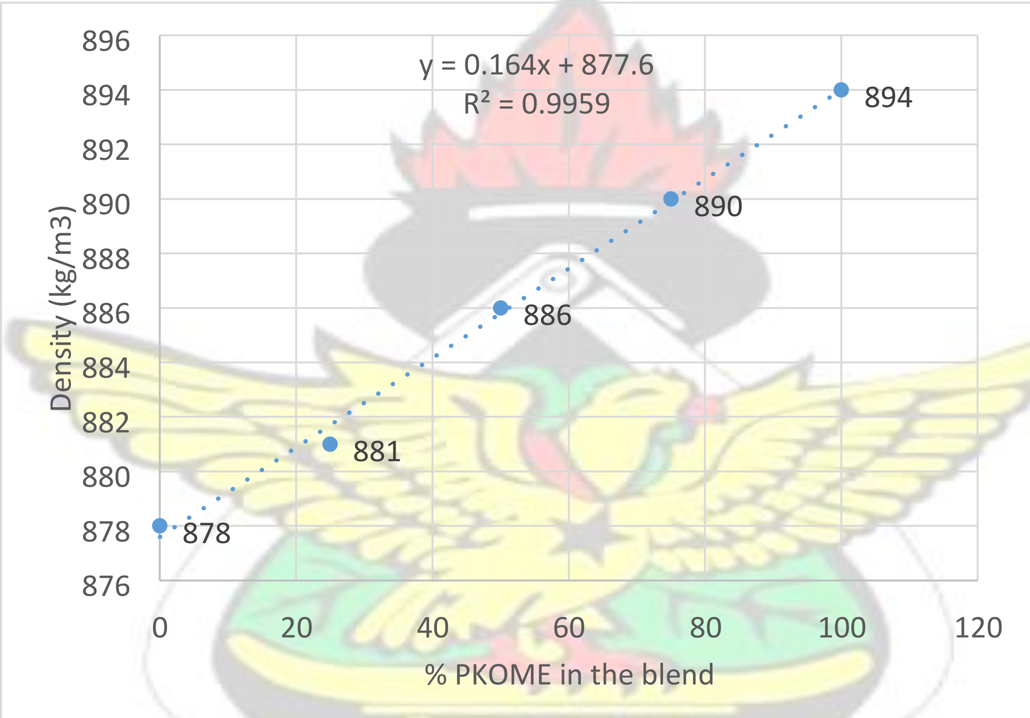


Figure 4.17 Density of PKOME-COME blends

It has also been established that the higher the chain length the lower the fuel density. Coconut oil and palm kernel oil are both considered as saturated oils. However, palm kernel oil has a higher degree of unsaturation (about 18%) compared to coconut oil (about 10%). The higher the degree of unsaturation the higher the density of the fuel is likely to be. This is why as seen in Figure 4.17, the higher the PKOME percentage in the blend the higher the density of the mixture and vice versa. From figure 4.17 an equation (4.5) was developed for Density of any PKOME-COME blend. It implies from the gradient of 0.164 that for every 1% increase in the percentage of PKOME the density of the blend will increase by 0.164 kg/m^3.

$$\text{Density (PKOME-COME)} = 0.164x + 877.6 \qquad (4.5)$$
$$0 \leq x \geq 100 \ (x = \%\ \text{PKOME})$$
$$(R^2 = 0.9959)$$

4.6.1.5.Best blend of PKOME-COME in comparison with petroleum diesel

All the blends have produced physiochemical properties similar to petro-diesel. However, the four most important properties for diesel fuel include viscosity, heating value, cetane number and density.

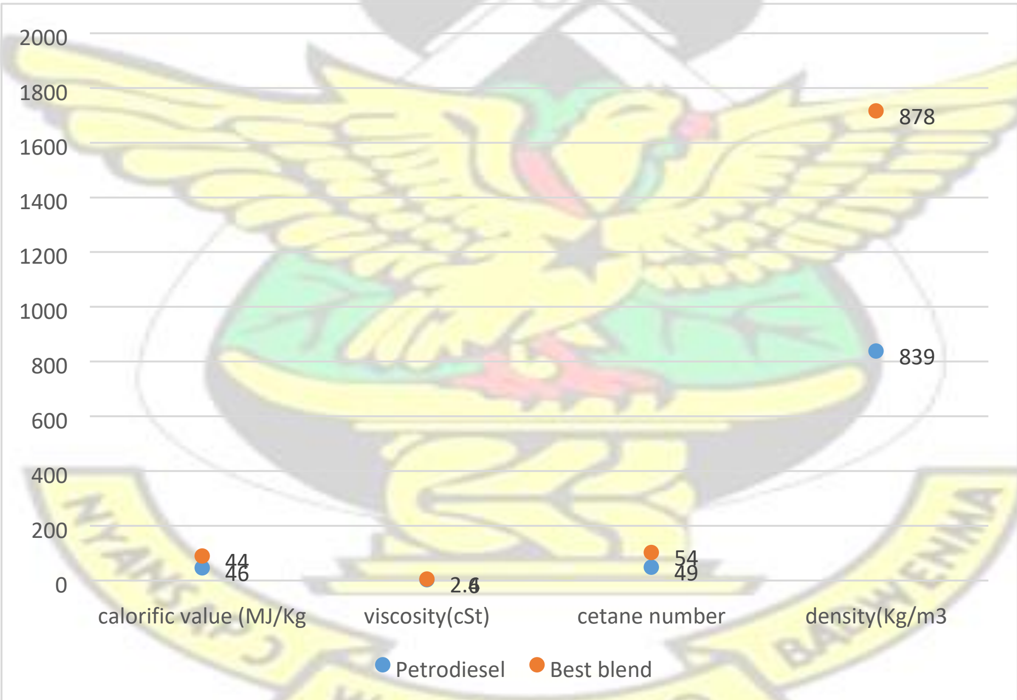


Figure 4.18 Comparison of best PKOME-COME blend properties with petroleum diesel.

Design expert, a design of experiment tool, was used to predict the best blend for

COME and PKOME. Blend of COME (35%) with PKOME (65%) gave the best fuel properties with a desirability of 62.6%. As depicted by Figure 4.18, fuel properties of the blend are very close to petroleum diesel where the cetane number of the best blend (54) was found to be better than petrodiesel (49). The greatest disparity lie with the densities with the best blend having a higher density or mass per unit volume (878 kg/m^3) compared to petrodiesel of 839 kg/m^3. High densities are not an issue with diesel engines.

4.6.2. Effects of PKOME-COME Blends on Emissions

Emissions and fuel consumption analysis were conducted through engine runs for specified blends of PKOME and COME. The results are depicted in Table 4.16.

Table 4.16 engine performance results for PKOME-COME blends

Run	**Component1 A: COME (%)**	**Component2 B: PKOME (%)**	**Response1 BSEC (MJ/kW-h)**	**Response2 CO (Vol. %)**	**Response3 HC(ppm)**	**Response4 NOx (ppm)**
1	0.00	100.00	14.6	0.69	69	244
2	25.00	75.00	14.8	0.53	59	205
3	**75.00**	**25.00**	**15.4**	**0.39**	**45**	**146**
4	50.00	50.00	15.1	0.45	40	180
5	100.00	0.00	15.5	0.32	39	140

4.6.2.1. Brake specific energy consumption

Brake specific energy consumption is a measure of rate of fuel consumption and the higher the BSEC the lesser the energy content in the fuel.

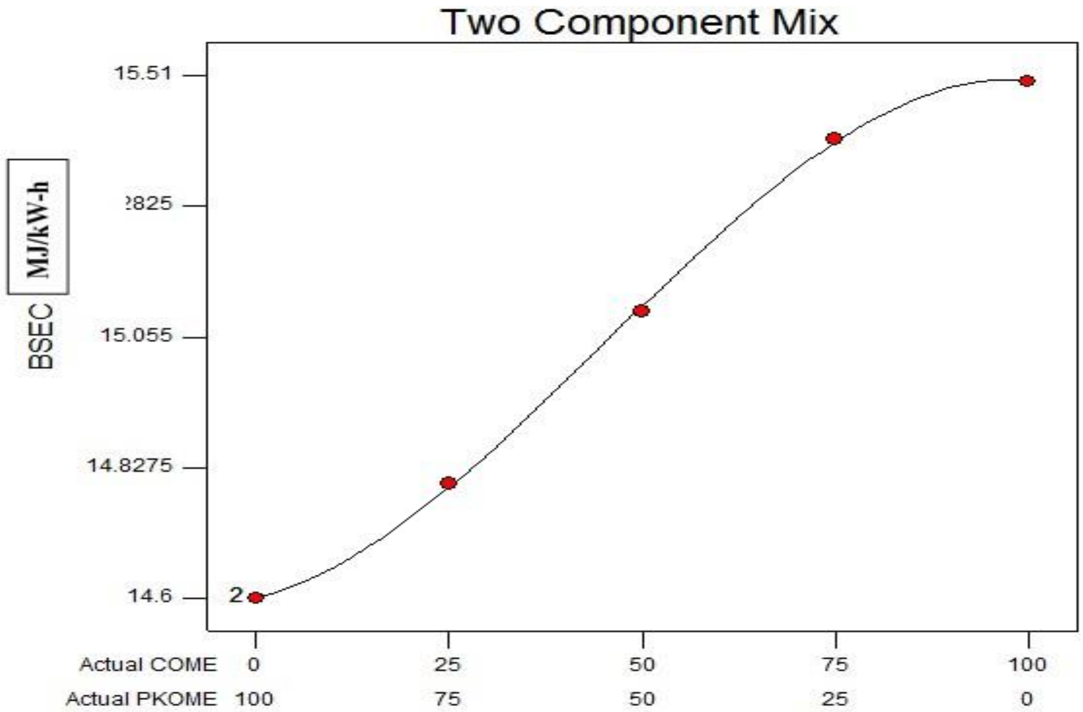


Figure 4.19 BSEC of PKOME-COME blends

The higher the COME percentage the worst the fuel consumption of the mixture. This proves that PKOME which has the higher calorific value can be used to improve brake specific energy consumption of COME (Figure 4.19).

4.6.2.2.Carbon monoxide and Hydrocarbon emissions

Maximum CO emissions (0.69 Vol.%) were obtained with 100% PKOME but as the COME component were increased to about 75% the COME emissions dwindled to 0.39Vol.% (Figure 4.20). Similar results were obtained for HC emissions.

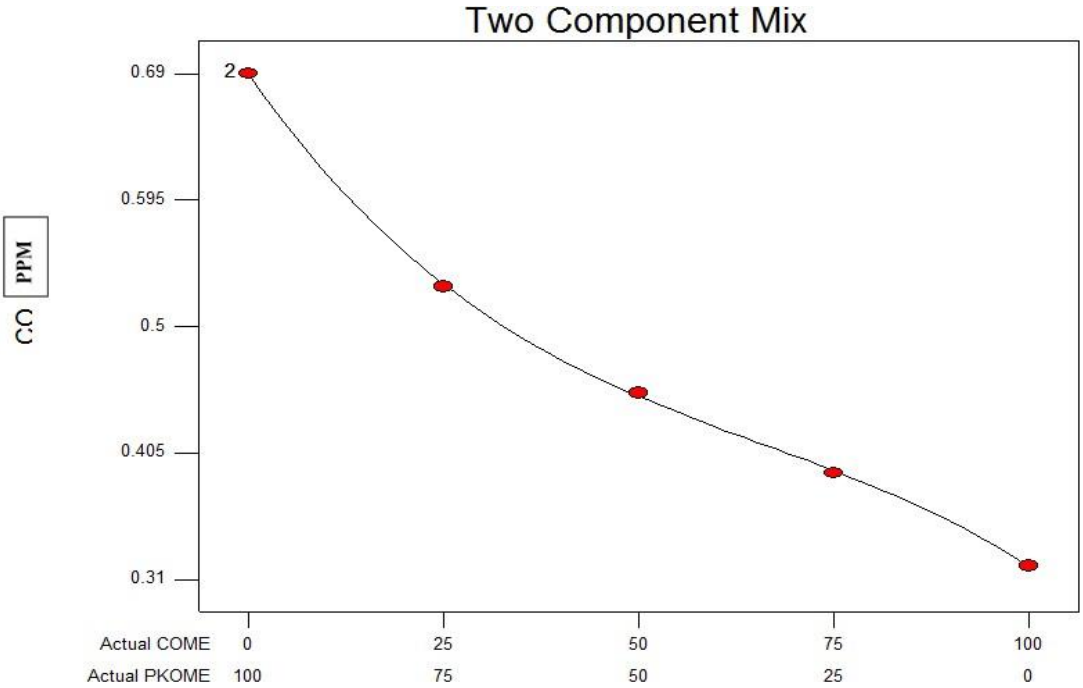


Figure 4.20 CO emissions of PKOME-COME blends

4.6.2.3.NOx emissions

NOx emissions as explained earlier are the nemesis of biodiesel emissions and the only emission element that surges with use of biodiesel. The results however prove that blending 25% PKOME with 75% of COME can lessen NOx emissions (Figure 4.21). Blending 25% PKOME with 75% COME lessened NOx emissions from 244 ppm to 140 ppm (43% reduction).

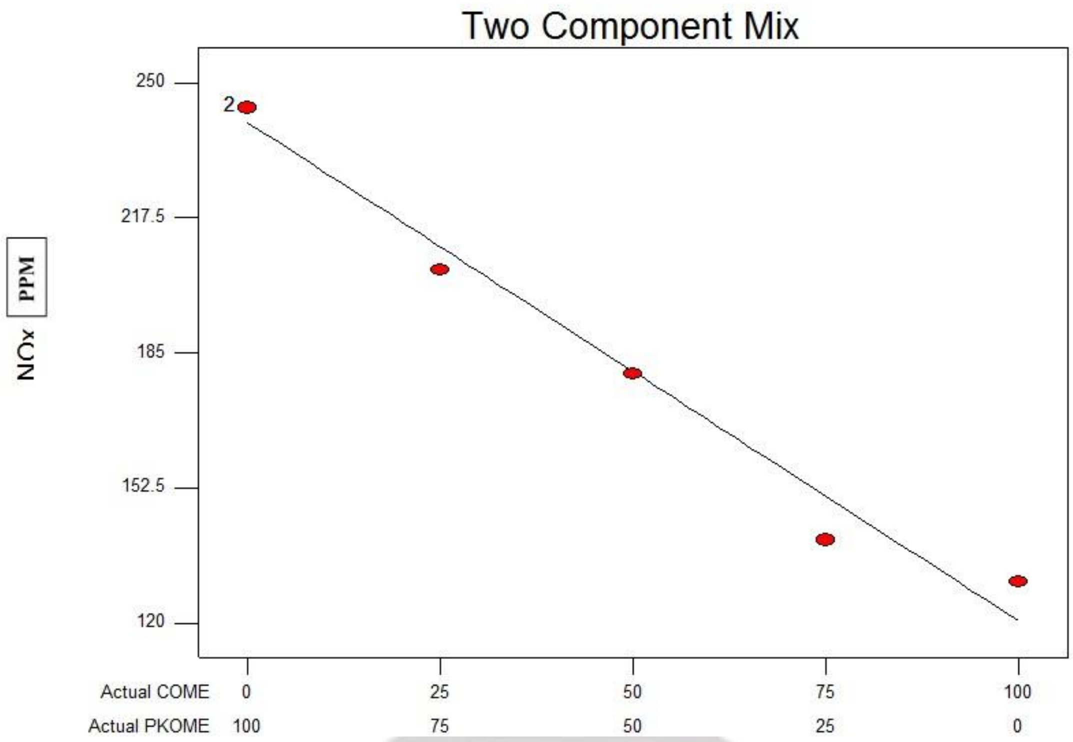


Figure 4.21 NOx emissions of PKOME-COME blends

4.6.3. Effects of JCME-COME Blends on Properties

The results obtained from the blends of JCME and COME at different percentages is presented in Table 4.17.

Table 4.17 physiochemical properties of JCME-COME blends

Run	Component 1 A: JCME (%)	Component2 B: COME (%)	Response1 Calorific Value (MJ/kW-h)	Response2 Viscosity (Cst)	Response3 Density (kg/m^3)	Response 4 Cetane Number
1	0.00	100.00	42	2.4	878	55
2	25.00	75.00	42	2.5	884	55
3	75.00	25.00	42	2.9	894	52
5	50.00	50.00	42	2.6	888	54
6	100.00	0.00	42	3.1	898	52

4.6.3.1.Viscosity variation with blend

Generally high viscosities lead to poorer fuel atomization and narrower injection spray angle. This leads to poor combustion and increased dilution. Thus the lower the viscosity the better. Viscosity of the JCME-COME component mix improved as COME percentage increased in the mixture (Figure 4.22)

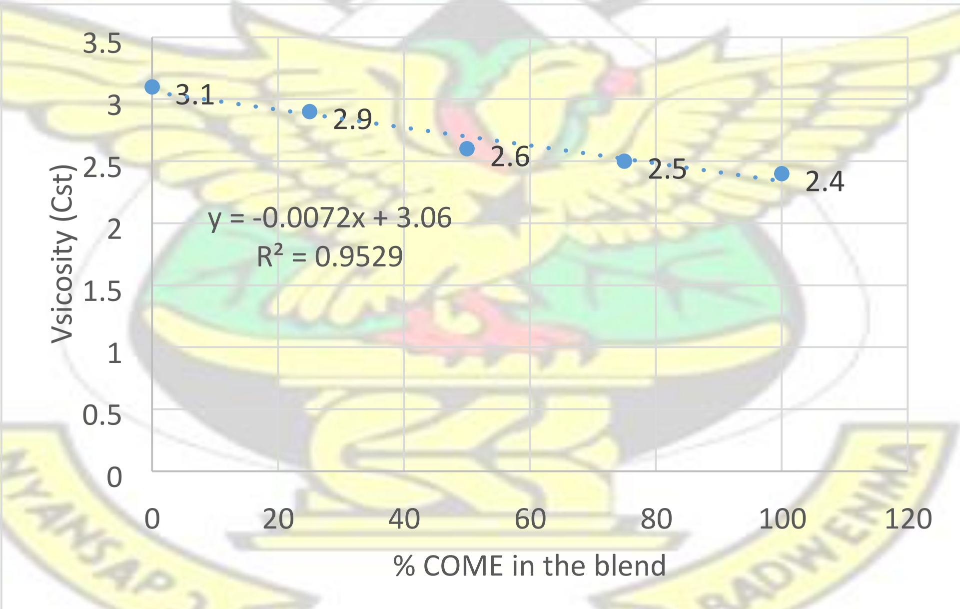


Figure 4.22 Viscosity of JCME-COME blends

. This is primarily because the sample of COME used originally had a low viscosity. Best blend for optimum viscosity was 25% JCME and 75% COME at approximately 2.3Cst (or mm^2/s) comparable to petroleum diesel viscosity of 3.2Cst. Equation 4.6 shows equation developed for viscosity of any JCME-COME blend. For every 1%

increase in the COME percentage the viscosity of the blend reduces by 0.0072Cst.

Viscosity (JCME-COME) = -0.0072x + 3.06 (4.6)

$0 \leq x \geq 100$ (x = % PKOME)
(R^2 = 0.9529)

4.6.3.2.Calorific value variation with blend

Calorific values were obtained for JCME, COME and their blends. Since both fuels recorded the same heating value of 42MJ/kg, their blend values did not change.

4.6.3.3.Cetane number variation with blend

Cetane number (CN) measures a fuel's auto ignition quality characteristics. Biodiesel mostly has a higher CN compared to petrodiesel because of its long-chain hydrocarbon groups. Also increasing degree of unsaturation leads to decreasing CN (Tesfa *et al.*, 2013; Ramírez-Verduzco, Rodríguez-Rodríguez & Jaramillo-Jacob, 2012; Ai-Fu & Liu, 2010).

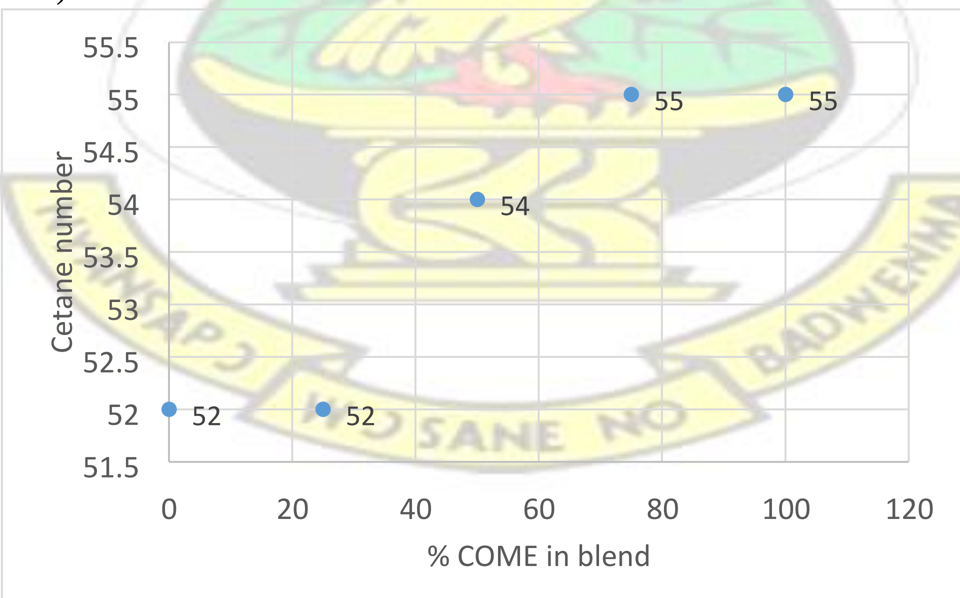


Figure 4.23 Cetane number of JCME-COME blends

From Figure 4.23, COME actually has the highest CN (55) compared to JCME (52). Addition of JCME to the blend thus decreases the CN of the blend. Jatropha oil contains about 75% unsaturated fat while coconut oil contains 10% unsaturated fats. Therefor the higher degree of unsaturation of JCME explains the higher the CN. Equation 4.7 developed for predicting cetane number of any JCME-COME blend is as shown.

Cetane number (JCME-COME) = 0.036x + 51.8 (4.7)

$0 \leq x \geq 100$ (x = % PKOME) (R^2 = 0.8804)

4.6.3.4.Density variation with blend

The air/fuel ratio and energy content within the combustion chamber are influenced largely by the fuel density. Biodiesel fuel density is strongly affected by the degree of unsaturation where the higher the unsaturation the denser the fuel.

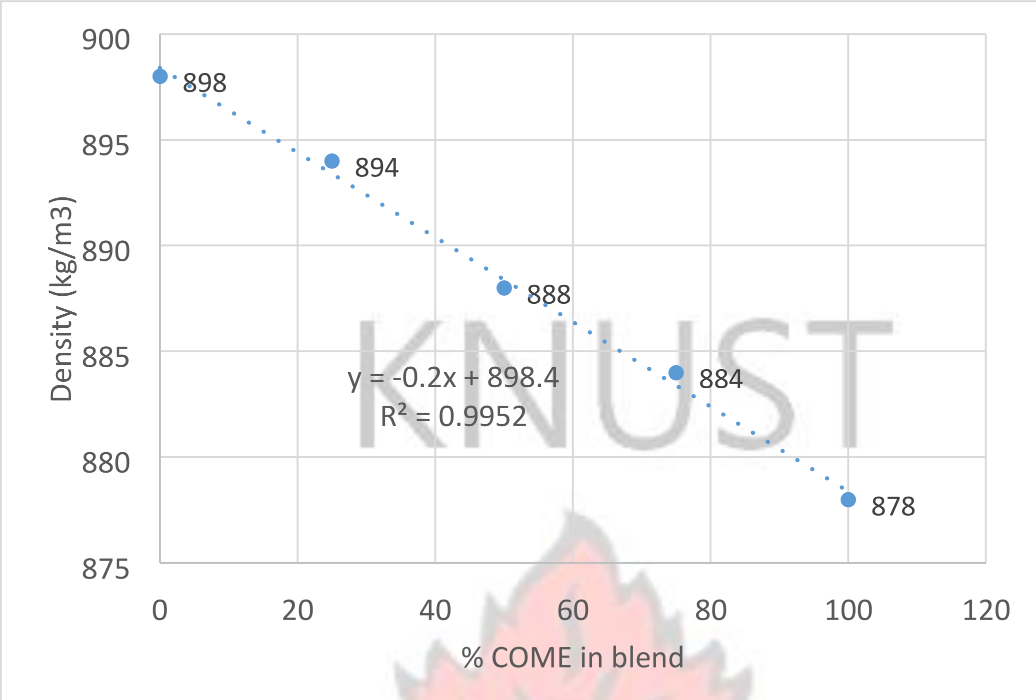


Figure 4.24 Density of JCME-COME blends

It has also been established that the higher the chain length the lower the fuel density. Coconut oil is considered as a highly saturated oil (90% degree of saturation and 10% unsaturation). But the degree of unsaturation of Jatropha oil is about 75% which explains why it is denser. The higher the degree of unsaturation the higher the density of the fuel is likely to be. This is why as seen in Figure 4.24, the higher the JCME percentage in the blend the higher the density of the mixture and vice versa. Equation 4.8 depicts the equation for the density of any JCME-COME blend. For every 1% increase of COME in the blend the density will reduce by 0.2 Kg/m^3.

Density (JCME-COME) = -0.2x + 898.4 (4.8) $0 \leq x \geq 100$ (x = % PKOME) ($R^2 = 0.9952$)

4.6.3.5.Best blend of JCME-COME in comparison with petroleum diesel

All the blends have produced physiochemical properties similar to petro-diesel. However, the four most important properties for diesel fuel include viscosity, heating value, cetane number and density.

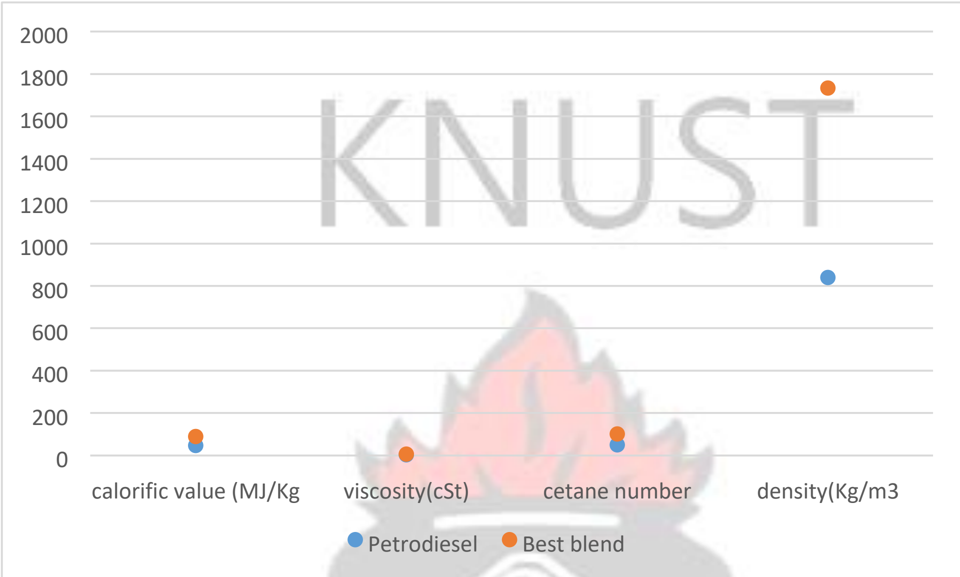


Figure 4.25 comparison of best JCME-COME blend properties with petroleum diesel.

Design expert, a design of experiment tool, was used to predict the best blend for JCME and COME. Blend of JCME (75%) with COME (25%) gave the best fuel properties with a desirability of 60.6%. As depicted by Figure 4.25, fuel properties of the optimum blend are very close to petroleum diesel where the cetane number of the best blend (52) was found to be better than petrodiesel (49). The greatest disparity lie with the densities with the best blend having a higher density or mass per unit volume of 894 kg/m^3 compared to petrodiesel of 839 kg/m^3. High densities are not an issue with diesel engines.

4.6.4. Effects of JCME-COME Blends on emission

Emissions and fuel consumption analysis were conducted through engine runs for specified blends of JCME and COME. The results are depicted in Table 4.18 and in Appendix D.

Table 4.18 engine performance results for JCME-COME blends

Run	Component 1 A: COME (%)	Compone nt2 B: JCME (%)	Respons e1 BSEC (MJ/kW -h)	Respons e2 CO (Vol. %)	Respons e3 HC(ppm)	Response 4 NOx (ppm)
1	0.00	100.00	12.6	0.22	60	310
2	**25.00**	**75.00**	**13**	**0.24**	**65**	**256**
3	75.00	25.00	13.7	0.3	82	180
4	50.00	50.00	14	0.28	75	207
5	100.00	0.00	15.5	0.32	39	130

4.6.4.1.Brake specific energy consumption variation with blend

Brake specific energy consumption is a measure of rate of fuel consumption and the higher the BSEC the lesser the energy content in the fuel. BSEC is best when it is lowest. The higher the COME percentage the worst the fuel consumption of the mixture (Figure 4.26).

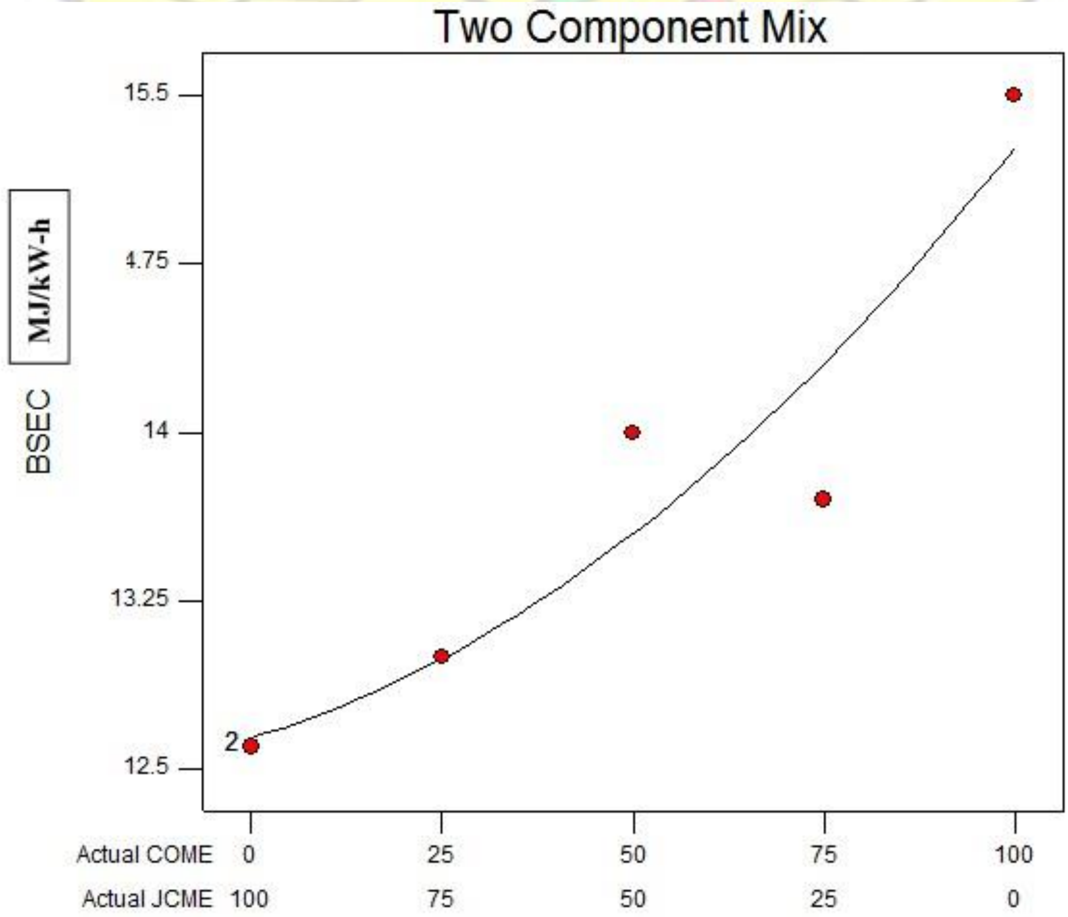


Figure 4.26 BSEC variation with JCME-COME blend

This proves that JCME which has the higher calorific value can be used to improve brake specific energy consumption of COME.

4.6.4.2.Carbon Monoxide and Hydrocarbon emissions

CO formation is as a result of incomplete combustion. This is when the flame front in the combustion chamber approaches a cool cylinder liner and is suddenly cooled down.

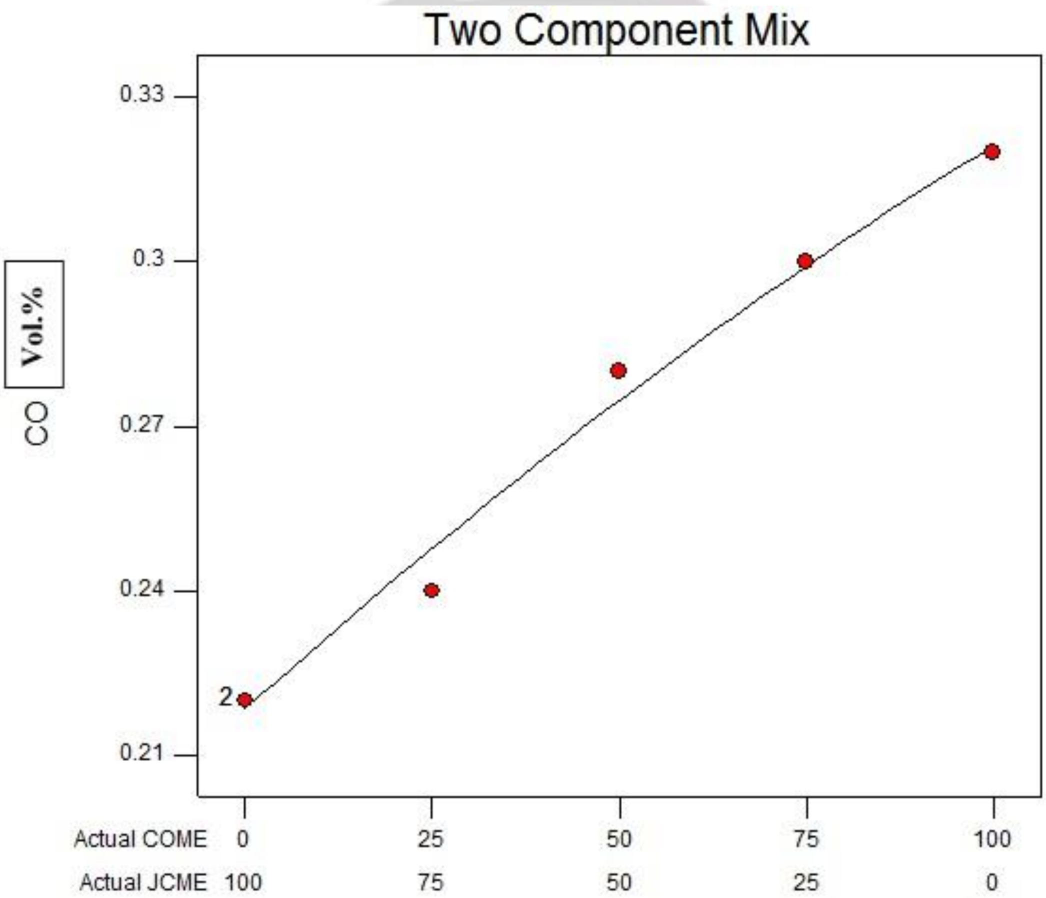


Figure 4.27 CO emission variation with JCME-COME blend

Maximum CO emissions (0.32 Vol.%) were obtained with 100% COME but as the JCME component were increased to about 75% the blend emissions reduced to 0.24Vol.% (Figure 4.27). Similar results were obtained for HC emissions.

4.6.4.3.Oxides of Nitrogen variation with blend

It is well known that NOx emission is affected by in-cylinder pressure, high temperatures and oxygen content of the fuel. Increasing JCME concentration in the blend reduces the NOx emissions (Figure 4.28).

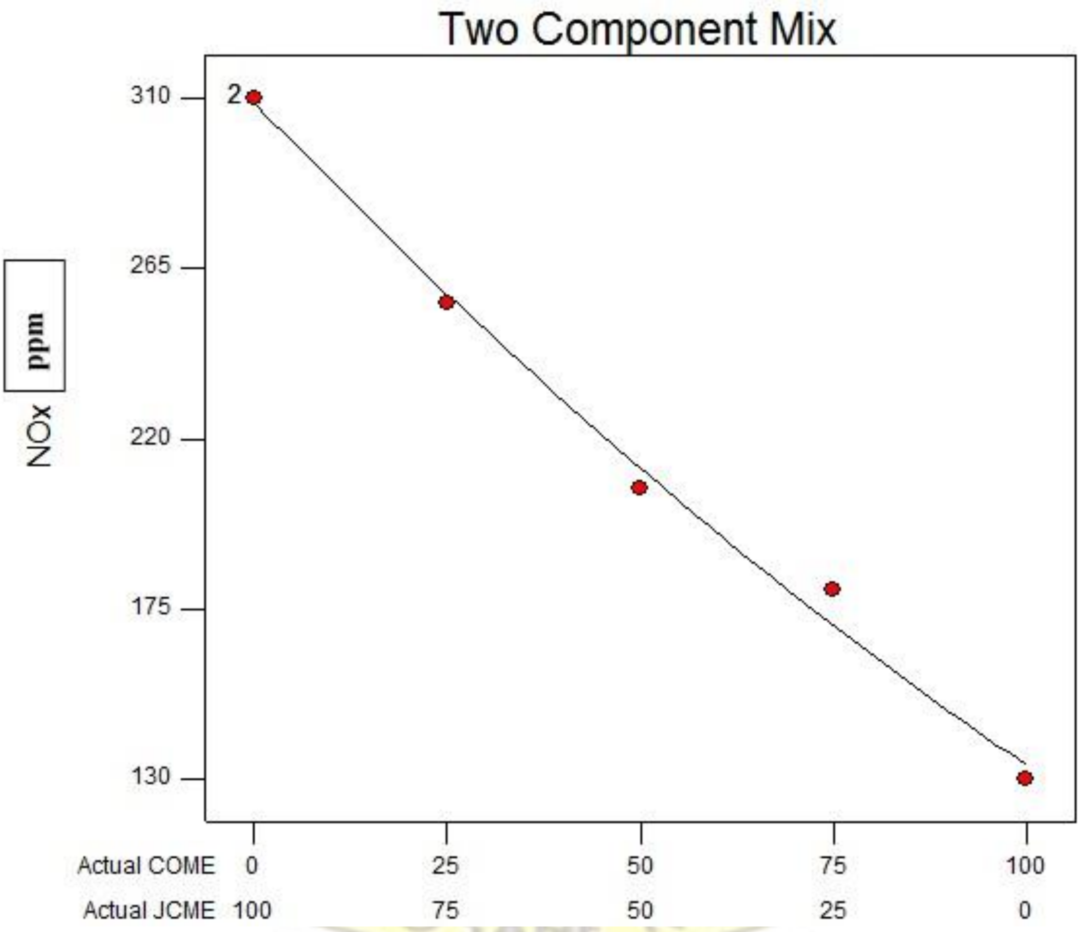


Figure 4.28 NOx emission variation with JCME-COME blends

4.6.5. Blends Emissions comparison

In terms of PKOME-COME (Fig. 4.29) the most desirable blend prediction and validation were obtained with 75% COME and 25% PKOME with a desirability of 97% but fuel consumption will surge as a result at 15.4 MJ/kW-h. The reverse combination of 75% PKOME and 25% COME should be considered if the goal is to maximize fuel consumption at the expense of emissions.

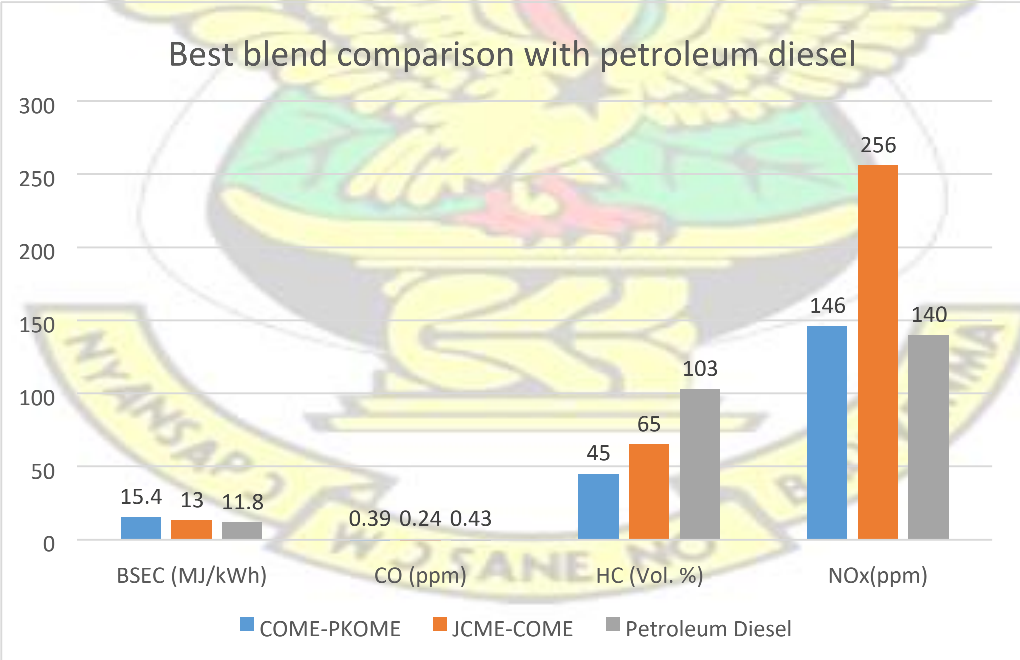


Figure 4.29 comparison of engine performance of best PKOME-COME blend, JCMECOME with petroleum diesel

In terms of JCME-COME the most desirable blend prediction and validation were obtained with 75% JCME and 25% COME with a desirability of 92%. Comparing best blends with petroleum diesel it is seen that Petroleum diesel has a lower fuel consumption compared to all the blends. It has already been explained that generally biodiesels have their fuel consumptions higher than petroleum diesel. The degree of difference being equivalent to the percentage of oxygen in biodiesel. In this case biodiesel contain approximately 10% more oxygen than petroleum diesel. Thus BSEC of JCME-COME at 13MJ/kg differs from petroleum diesel of 11.8 MJ/kg by approximately 10%.

All the biodiesel blends recorded lower CO (PKOME-COME=0.39 ppm, JCMECOME=0.29 ppm) emissions compared with petroleum diesel (0.43 ppm). The trend was similar for HC emissions with PKOME-COME blend recording HC emissions of

128% lower than petroleum diesel. The disadvantage of biodiesel still lies with the NOx emissions since the higher concentration of oxygen in biodiesel makes its NOx emissions higher than petroleum diesel. However, NOx emissions of COME-PKOME (146 ppm) obtained was 140 ppm. This implies that blending biodiesel fuels of different feedstocks could be the key to reducing NOx emissions of biodiesel fuelled engines.

4.7. Engine performance of biodiesel

Experimental results of experiments carried out on engine performance is shown here. The results at different speeds for petroleum diesel and the three biodiesel of PKOME, COME and JCME are presented. Power, torque, BSFC and efficiency at different engine speeds were considered. The test engine was first tested with petroleum diesel in order to establish a base line for comparison. Each of the fuels were run at 1500, 1800, 2100, 2400, 2700, 3000, 3300, 3600, 3900, 4200 and 4500 rpm. Tables 4.19 to 4.22 show results of each run.

Table 4.19 brake power recorded at varying speeds for biodiesel and petrodiesel

Engine speed (rpm)	**Power (kW)**			
	PKOME	COME	JCME	DIESEL
1500	41	40	41	42
1800	50	49	49	52
2100	59	58	58	61
2400	69	68	68	72
2700	79	77	78	82
3000	88	86	87	93
3300	97	95	95	104
3600	104	103	102	113
3900	111	110	110	121
4200	119	117	117	128
4500	116	115	116	127

Table 4.20 Torque recorded at varying speeds for biodiesel and petrodiesel

Engine speed (rpm)	**Torque (Nm)**			
	PKOME	COME	JCME	DIESEL
1500	260	256	258	270
1800	264	259	260	275
2100	268	263	265	279
2400	274	270	271	285
2700	278	273	274	290
3000	280	275	276	296
3300	280	274	275	300
3600	276	272	272	300
3900	272	270	269	296
4200	270	267	267	290
4500	247	244	245	270

Table 4.21 BSFC recorded at varying speeds for biodiesel and petrodiesel

Engine speeds (rpm)	**BSFC (g/kW-h)**			
	PKOME	COME	JCME	DIESEL
1500	264	269	266	255
1800	217	221	220	208
2100	183	187	185	176
2400	157	159	159	151
2700	137	140	139	132
3000	123	125	124	116
3300	112	114	113	104
3600	104	105	105	95
3900	97	98	98	89
4200	91	92	92	85
4500	93	94	93	85

Table 4.22 Thermal efficiency recorded at varying speeds for biodiesel and petrodiesel

Engine speed (rpm)	**Thermal Efficiency (%)**			
	PKOME	COME	JCME	DIESEL
1500	31	32	32	31
1800	38	39	39	38
2100	45	46	46	44
2400	52	54	54	52
2700	60	61	61	59
3000	67	68	69	67

3300	73	75	75	75
3600	79	81	81	82
3900	84	88	87	88
4200	90	93	93	92
4500	88	91	92	92

4.7.1. Power and Torque analysis

Power and torque analysis were carried out for the test engine with petroleum diesel and biodiesel. Figure 4.30 shows the differences in the brake power with engine speed of the test engine operated with petroleum diesel and three other biodiesel produced from oils of coconut, palm kernel and Jatropha.

The engine brake power (*BP*) in kW was calculated as:

$$BP = \frac{T}{1000} \times \frac{2\pi \times N}{60} \quad (4.9)$$

Where:

T = Measured brake torque of the engine (Nm), N = Measured engine speed (rpm).

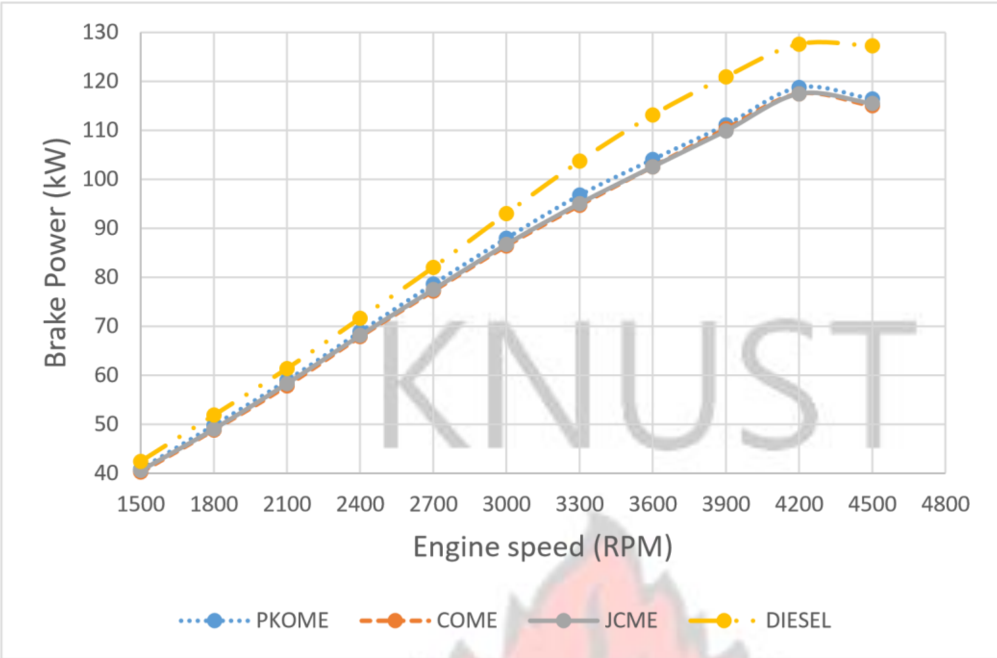


Figure 4.30 power output against engine speed with petrodiesel and biodiesels

At an engine speed of about 4200 rpm, the brake power of all fuels including petroleum diesel reached their peak value. Brake power of the test engine run on petroleum diesel was higher than for any of the biodiesel run. Petroleum diesel recorded 5% more power than palm kernel oil biodiesel at 4200 rpm. This is because of higher torque values obtained for petroleum diesel. Generally, brake power for all fuels increased to a maximum at 4200 rpm and decreased. This is because friction power increases with engine speed to a higher power and becomes dominant at higher engine speeds.

Between 3000 and 3600 rpm, the test engine yielded maximum torque for all fuels from Figure 4.31. The minimum torque occurred between 1500 and 2100 rpm. Torque for petroleum diesel was higher than that for all biodiesel fuels tested. The reason is attributed to the lower calorific value of biodiesel.

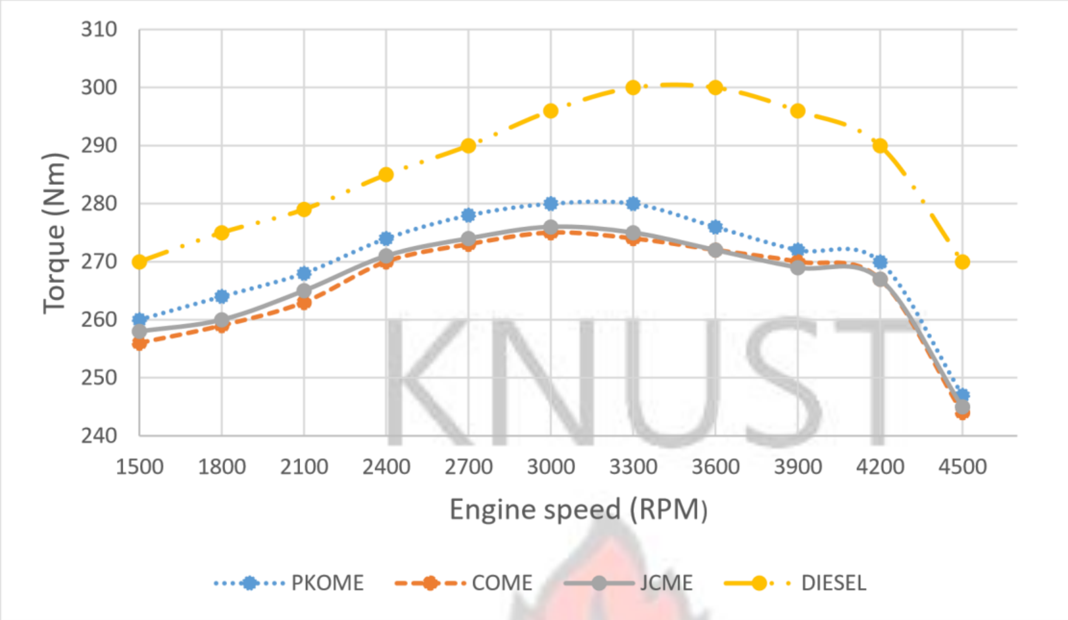


Figure 4.31 Torque output against engine speed with petrodiesel and biodiesels

From the Figure 4.31, peak torques for biodiesel occurred at lower engine speeds. It can be noticed from Figure 4.31 that as engine speeds increases beyond 3300 rpm torque begin to decline for all fuels. Thus as engine speed increases beyond a certain speed, torque reaches a maximum and then decreases as shown. Torque decreases because the engine is unable to ingest a full charge of air at higher speeds.

4.7.2. Energy Consumption and Thermal Efficiency

The brake specific fuel consumption (BSFC) in kgh^{-1}kW^{-1} was calculated as**:**

$$BSFC = \frac{m_f}{BP} \times 3600 \quad (4.10)$$

Where: mf= Measured fuel consumption (kg/s)

Figure 4.32 shows the variations in the BSFC in g/kWh for both petroleum diesel and biodiesel against engine speed. Generally, BSFC decreased as engine speed increased.

For all fuels tested, the BSFC decreased to a minimum at 4200 RPM and then began to increase. Fuel consumption increased at high speeds because of frictional losses.

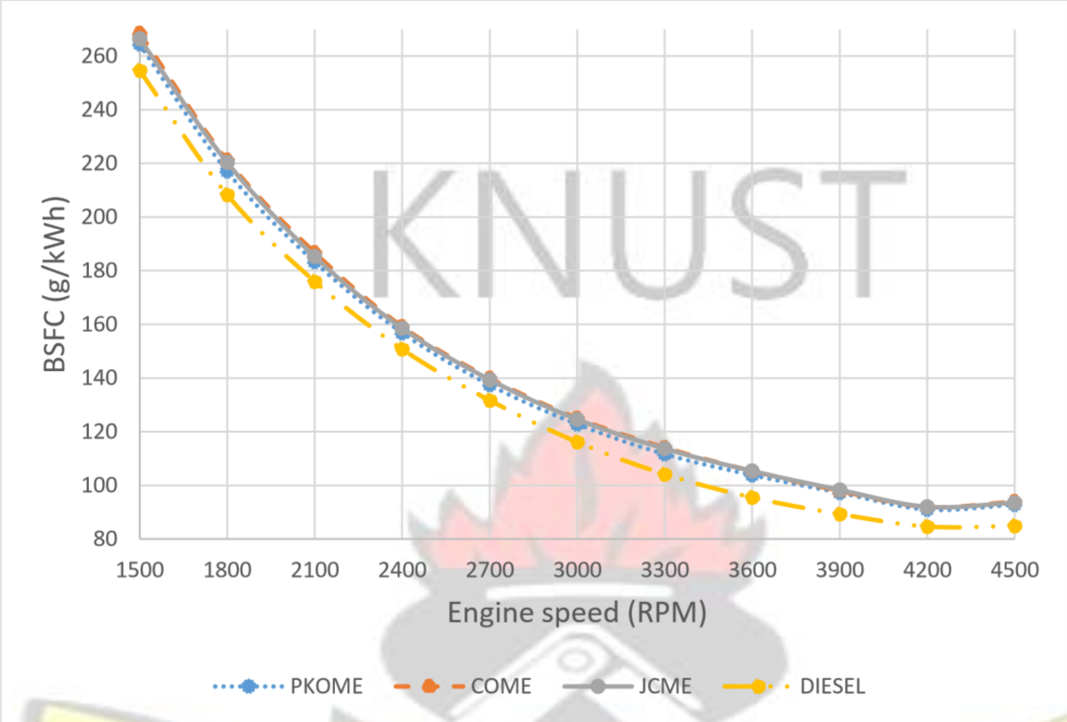


Figure 4.32 BSFC measured against engine speed with petrodiesel and biodiesels

BSFC is high at low engine speeds because at low engine speeds there is more time per cycle which allows for significant heat losses leading to high fuel consumptions.

The BSFC of petroleum diesel was found to be much better than the biodiesels. PKOME however recorded much lower BSFC compared to JCME and COME. On the average the BSFC of biodiesel was more than petroleum diesel by about 5%. The highest BSFC was obtained using biodiesel from coconut oil.

The brake thermal efficiency (Eff, %) was calculated as

$$Eff = \frac{BP \times 1000}{m_f \times C.V.} \times 100 \qquad (4.11)$$

Where:
C. V = calorific value of the fuel (J/kg)

Brake thermal efficiency for petroleum diesel and biodiesel against engine speed are shown in Figure 4.33.

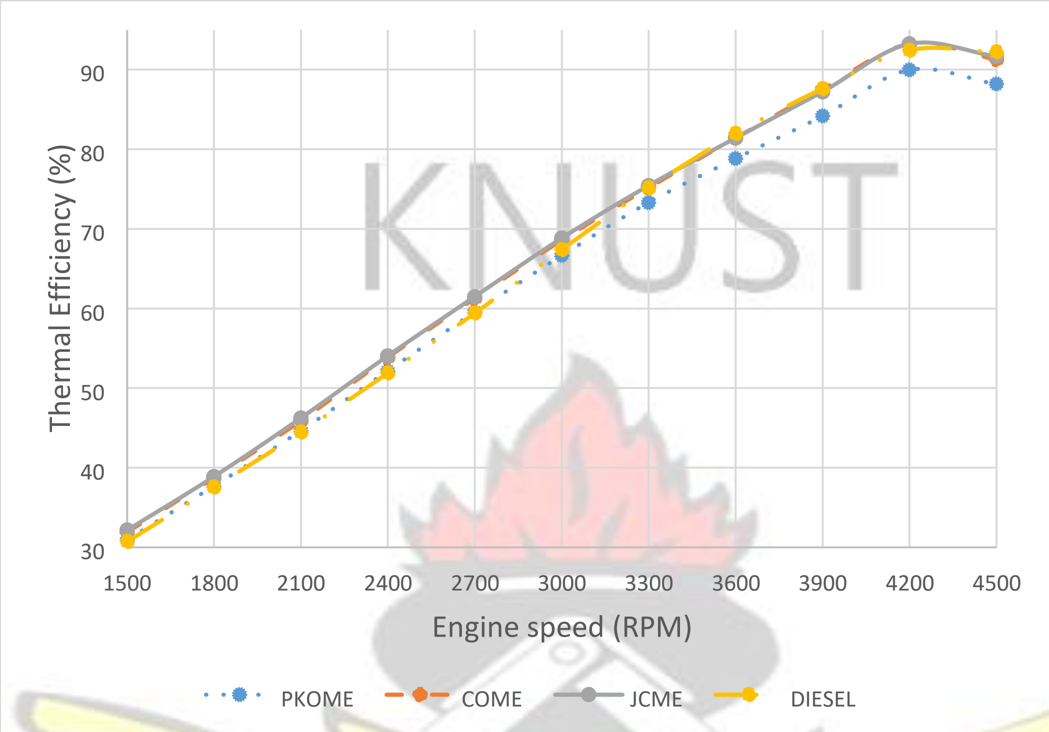


Figure 4.33 Thermal efficiency measured against engine speed with petrodiesel and biodiesels

The maximum thermal efficiency for petroleum diesel and biodiesel were recorded at engine speed of 4200 rpm. It is observed that at initial speeds biodiesel recorded higher thermal efficiencies compared with petroleum diesel. The ratio of the brake power developed by the engine and the energy released per unit time due to complete combustion of fuel is what is referred to as brake thermal efficiency. At lower engine speeds, not all fuel molecules may find an oxygen molecule to combine with but since biodiesel has an additional oxygen molecule it is easier for it combust.

4.8. Cost Analysis of Biodiesel Production in Ghana

The data obtained so far shows biodiesel has similar characteristics as petroleum diesel and is a viable alternative. However, it will be cost effective to know the cheapest alternative among the feedstocks available in Ghana. This section presents cost analysis of biodiesel feedstock options in Ghana. The cost analysis follow a procedure to determine a unit cost per gallon of biodiesel. It is first important to analyse factors that affect cost of biodiesel production. Variable costs of each of the factors that affect biodiesel production is as shown in Table 4.23.

Table 4.23 biodiesel production cost

Variable Costs	**Bulk Cost**	**Cost Per Unit**	**Used Per Batch**	**Per Batch**	**Per Gallon**
Methanol (per gallon)	$192.50/55 gallon	$3.5	8	$28.00	$0.70
Catalyst (KOH) (per gram)	$65/50# bag (22,727 grams)	$0.00296	1890	$5.59	$0.14
Electricity (per Kilowatt Hours)	25 kWh @ $0.10/kWh	$0.1	25	$2.50	$0.06
Sulphuric Acid(per millimetres)	$33.18/ 2500 mL	$0.0130	150	$1.95	$0.05
Water (per gallon)	$0.01/gal	$0.010	40	$0.40	$0.01
Total				**$38.44**	**$0.96**

On the average the total cost involved in producing a gallon of biodiesel if a biodiesel reactor is to be used will amount to $ 0.96 per gallon.

Table 4.24 shows the overall cost of production of one gallon of biodiesel from four different feedstocks. The highest biodiesel price estimation was obtained for coconut oil biodiesel with the lowest for palm oil biodiesel followed by palm kernel oil biodiesel.

Table 4.24 biodiesel production total cost

Vegetable Oil	Cost of oil per Gallon	Cost of biodiesel production per gallon	Cost per gallon (**$**)
Palm kernel oil	$3.17	**$0.96**	$4.13
Coconut oil	$4.13	**$0.96**	$5.09
Jatropha	$3.2	**$0.96**	$4.16

Palm oil	$3.16	**$0.96**	$4.12

Currently the local price of petroleum diesel in Ghana as at 24th July, 2015 is $3.33 per gallon. It is clear from Table 4.24 that unless the price of petroleum diesel reaches at least $5.00 per gallon, producing biodiesel for commercial purposes will not be viable. However, another option will be for government to provide tax incentives considering biodiesel is environmentally friendly and stands the chance of earning the country carbon credits according to the Kyoto protocol.

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Oils from coconut, palm kernel and Jatropha were used as feedstocks for the production of biodiesel to investigate optimum biodiesel production to obtain high yield, best quality of biodiesel and best engine performance. The base-catalyst was varied, methanol to oil molar ratio were also varied to obtain optimum parameters for each feedstock. For each of the feedstock, the biodiesel yield increased with increase catalyst concentration.

- The highest yield was obtained with 1% catalyst concentration for all. At 1% base catalyst (NaOH) concentration a yield of 98%, 96% and 95% for PKOME, JCME and COME respectively were obtained at 6:1 methanol to oil ratio.
- The results show the higher the sulphuric acid concentration the lower the kinematic viscosity of PKOME. The Kinematic viscosity of PKOME was reduced from 5.7 mm^2/s to 3.7 mm^2/s with the addition of 1% sulphuric acid.
- Analyses of the three oils showed that, rise in ratio of methanol to oil causes a equivalent rise in yield till the best yield is arrived at.

Palm kernel oil biodiesel and coconut oil biodiesel were blended in proportions of 100%, 75%, 50%, 25% and 0% by volume to determine optimum physiochemical properties and engine performance. Coconut oil biodiesel and Jatropha biodiesel were also blended in the same proportions.

- In terms of emissions the most desirable blend prediction obtained was 75% JCME and 25% COME by volume. The fuel consumption result for this blend was 13MJ/kW-h, with CO, HC and NOx emission values of 0.24%, 65 ppm and 256 ppm respectively. Compared to petroleum diesel this represents a 44% reduction in CO emissions and 37% reduction in HC emissions.
- The result prove that blending biodiesel of different feedstocks can improve their engine performance and emissions. The emission results were far better than for petroleum diesel.

An experimental matrix was designed to optimize engine parameters by examining the influence of injection timing only, injection pressure only and their combined influence on fuel consumption and emissions of CO, HC and NOx of coconut, palm kernel and Jatropha oil biodiesel fuelled engine.

- For PKOME, fuel injection pressure of 250 bar and 3^0 advance of injection timing produced the lowest fuel consumption and least exhaust emissions. At these points minimum BSEC of 13.4 MJ/kW-h, CO of 0.27 ppm and HC of 57 Vol. % at the expense of high emissions of NOx at 340 ppm were recorded. The effect of varying injection timing and pressure on fuel consumption was substantial. Injection advance lowered the fuel consumption while retardation increased fuel consumption. For example, for PKOME fuelled engine, when the injection timing was retarded by 6 CAD the BSEC was 15MJ/kw-h. But, this reduced to 13 MJ/kw-h when the timing was advanced to 9 CAD. The interactive effect of injection pressure and timing on BSEC were found not to be significant. Advancing injection timing reduced CO formation while retardation however increases CO formation. Injection timing therefore requires modification for use of PKOME if less CO formation is expected. Similarly increased injection pressure resulted in less CO formation.
- For COME, 250 bar of injection pressure and 3^0 of injection advance were found with the lowest fuel consumption and least exhaust emissions. At these points BSEC of 13.8MJ/kW-h), CO of 0.24ppm, HC of 74Vol. % and NOx of 176 ppm were recorded. Injection timing parameter did not have significant impact on COME engine emissions since the p-value of 0.5844 was far above the primary value of 0.05 that shows significance. While injection pressure increased, HC emissions reduced. The combined influence of injection timing and injection pressure was significant in HC emissions for COME.
- The optimal values for JCME were found to be at injection pressure of 200 bar and injection timing of $3\ ^0$. The BSEC recorded at this optimal match was 14 MJ/kW-h with CO of 0.26 Vol.%, HC of 71 ppm and NOx of 182 ppm. Both

injection timing and pressure were found to be significant on fuel consumption. There is continuous reduction in fuel consumption as injection pressure is increased. CO emissions reduced with injection timing advance and vice versa. The higher the injection pressure the lower the CO formation. HC emission lessened with increase injection pressure.

- It was also noticed that after every 50 hours of engine run, the fuel filters became clogged and had to be replaced. As compared to petrodiesel engine, fuel filters for biodiesel fuelled engines have to be changed twice as much frequently.

Petroleum diesel brake power and torque were found higher than biodiesel at all engine speeds. However, at initial engine speeds biodiesel recorded higher thermal efficiencies of about 39% compared with petroleum diesel of 38% at 1800 rpm.

5.2.Recommendations

This work has shown that engine optimization can be utilized in improving engine performance of biodiesel engines. However, NOx emissions for engine fuelled with biodiesel is higher than petroleum diesel fuelled engine emissions no matter the blend or optimisation. This work achieved a reduction of NOx emissions but in order to reduce emissions, further work on varying EGR ratios should be carried out. This work only considered oils from palm kernel, Jatropha and coconut with their methyl ester blends. However, since there are many feed stocks for biodiesel production, further works should consider blending other feedstocks to improve physiochemical properties and engine performance. There is also the need to conduct tests that will test durability of engine parts as a result of biodiesel usage. The durability test should consider material compatibility of the fuel system lines as well as examining engine oil in terms of viscosity and density to determine dilution after at 60 hours intervals.

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APPENDIX A

Injection variation results for palm kernel oil biodiesel-full factorial design with JMP design matrix

	Pattern	INJECTION TIMING(CAD)	INJECTION PRESSURE	BSEC (MJ/kWh)	CO (Vol.%)	HC(ppm)	NOx(ppm)
1	11	-6	150	15	0.79	92	140
2	12	-6	175	14.8	0.74	81	145
3	13	-6	200	14.5	0.56	71	155
4	14	-6	225	14.4	0.51	67	173
5	15	-6	250	14.2	0.49	64	179
6	21	-3	150	14.8	0.76	79	168
7	22	-3	175	14.6	0.72	77	178
8	23	-3	200	14.2	0.5	69	193
9	24	-3	225	13.9	0.47	63	223
10	25	-3	250	14.2	0.7	63	229
11	31	0	150	14.6	0.69	75	244
12	32	0	175	14.4	0.56	73	251
13	33	0	200	14	0.46	67	266
14	34	0	225	13.8	0.41	61	292
15	35	0	250	13.6	0.38	58	300
16	41	3	150	14.2	0.5	70	280
17	42	3	175	14	0.45	67	300
18	43	3	200	13.8	0.38	65	308
19	44	3	225	13.6	0.29	58	330
20	45	3	250	13.4	0.27	56	340
21	51	6	150	14	0.45	66	360
22	52	6	175	13.8	0.37	63	367
23	53	6	200	13.7	0.35	59	399
24	54	6	225	13.6	0.28	57	409
25	55	6	250	13.4	0.26	55	420
26	61	9	150	13.7	0.42	62	410
27	62	9	175	13.5	0.35	60	425
28	63	9	200	13.3	0.33	57	438
29	64	9	225	13.2	0.3	55	450
30	65	9	250	13	0.26	52	470

APPENDIX B

Injection timing variation results for Coconut oil biodiesel-full factorial design with JMP design matrix

	Pattern	INJECTION TIMING(CAD)	INJECTION PRESSURE(Bar)	BSEC (MJ/kWh)	CO (Vol.%)	HC(ppm)	NOx(ppm)
1	11	-6	150	15.5	0.4	105	100
2	12	-6	175	15	0.38	97	104
3	13	-6	200	14.8	0.36	92	109
4	14	-6	225	14.7	0.34	88	115
5	15	-6	250	14.5	0.32	81	125
6	21	-3	150	15.2	0.36	100	121
7	22	-3	175	14.9	0.34	91	126
8	23	-3	200	14.7	0.33	83	130
9	24	-3	225	14.4	0.31	79	135
10	25	-3	250	14.2	0.3	75	142
11	31	0	150	15	0.32	92	130
12	32	0	175	14.8	0.3	87	145
13	33	0	200	14.6	0.28	84	155
14	34	0	225	14.1	0.26	78	167
15	35	0	250	13.8	0.24	74	176
16	41	3	150	14.5	0.3	85	155
17	42	3	175	14.2	0.29	78	176
18	43	3	200	14	0.26	71	182
19	44	3	225	13.7	0.24	64	196
20	45	3	250	13.4	0.2	60	210
21	51	6	150	14.2	0.31	86	159
22	52	6	175	14.4	0.32	90	155
23	53	6	200	14.5	0.34	94	150
24	54	6	225	14.8	0.36	96	142
25	55	6	250	15	0.38	98	135
26	61	9	150	14.4	0.33	88	150
27	62	9	175	14.6	0.36	90	139
28	63	9	200	14.7	0.36	94	135
29	64	9	225	15	0.38	98	129
30	65	9	250	15.4	0.38	102	109

APPENDIX C

Injection parameter variations for Jatropha oil biodiesel-full factorial design with JMP design matrix

	Pattern	INJECTION TIMING(CAD)	INJECTION PRESSURE	BSEC (MJ/kWh)	CO (Vol.%)	HC(ppm)	NOx(ppm)
1	11	-6	150	14.7	0.82	80	135
2	12	-6	175	14.5	0.8	71	145
3	13	-6	200	14.3	0.75	68	150
4	14	-6	225	14	0.71	67	175
5	15	-6	250	13.9	0.7	64	180
6	21	-3	150	14	0.76	75	160
7	22	-3	175	13.7	0.7	71	180
8	23	-3	200	13.5	0.6	69	195
9	24	-3	225	13.2	0.56	65	220
10	25	-3	250	13	0.5	63	230
11	31	0	150	13.5	0.57	70	230
12	32	0	175	13.3	0.56	63	255
13	33	0	200	13.2	0.46	60	270
14	34	0	225	13	0.41	57	295
15	35	0	250	12.9	0.38	58	300
16	41	3	150	13	0.27	70	270
17	42	3	175	12.8	0.24	62	290
18	43	3	200	12.6	0.22	60	310
19	44	3	225	12.4	0.22	58	330
20	45	3	250	12.2	0.2	56	340
21	51	6	150	13.7	0.47	72	350
22	52	6	175	13.8	0.37	71	360
23	53	6	200	13.7	0.35	69	380
24	54	6	225	13.6	0.28	65	400
25	55	6	250	13.4	0.26	63	420
26	61	9	150	14	0.42	78	390
27	62	9	175	13.8	0.34	70	420
28	63	9	200	13.5	0.32	67	430
29	64	9	225	13.2	0.3	65	445
30	65	9	250	13	0.25	62	485

APPENDIX D

Experimental matrix for JCME-COME blends –results of full factorial design with Design Expert 7.0

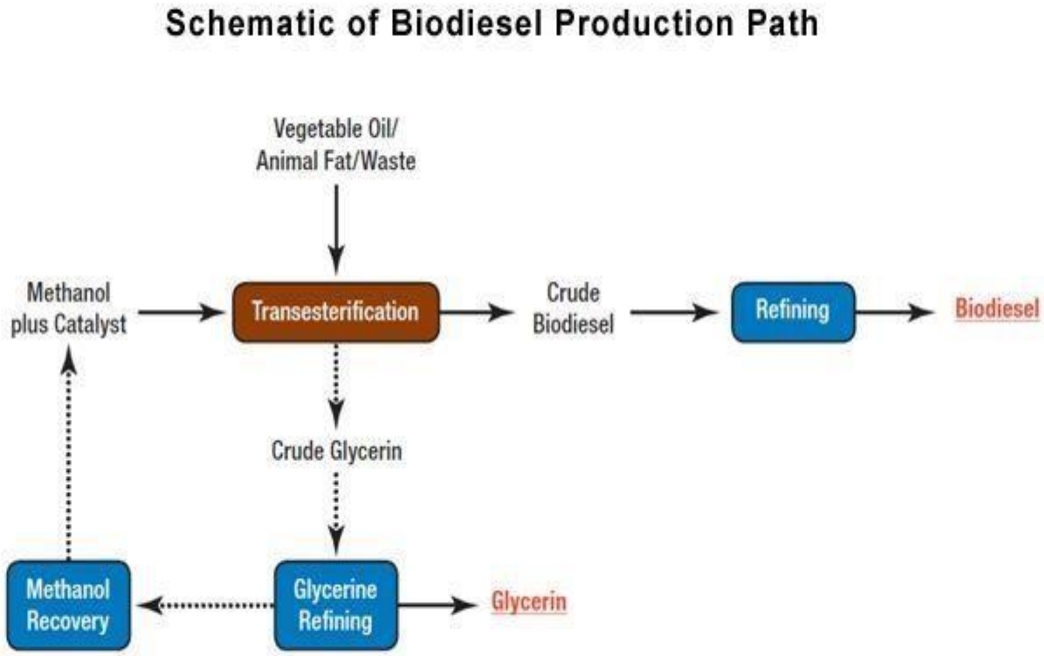
Std	Run	Block	Component 1 A:COME %	Component 2 B:JCME %	Response 1 BSEC MJ/kWh	Response 2 CO Vol.%	Response 3 HC ppm	Response 4 NOx ppm
6	1	Block 1	0.000	100.000	12.6	0.22	60	310
4	2	Block 1	25.000	75.000	13	0.24	65	256
5	3	Block 1	75.000	25.000	13.7	0.3	82	180
3	4	Block 1	0.000	100.000	12.6	0.22	60	310
2	5	Block 1	50.000	50.000	14	0.28	75	207
1	6	Block 1	100.000	0.000	15.5	0.32	92	130

APPENDIX E

Experimental matrix for PKOME-COME blends –results of full factorial design with Design Expert 7.0

Std	Run	Block	Component 1 A:COME %	Component 2 B:PKOME %	Response 1 BSEC MJ/kWh	Response 2 CO Vol.%	Response 3 HC ppm	Response 4 NOx ppm
6	1	Block 1	0.000	100.000	14.6	0.69	69	244
4	2	Block 1	25.000	75.000	14.8	0.53	79	205
5	3	Block 1	75.000	25.000	15.4	0.39	88	140
3	4	Block 1	0.000	100.000	14.6	0.69	69	244
2	5	Block 1	50.000	50.000	15.1	0.45	83	180
1	6	Block 1	100.000	0.000	15.5	0.32	92	130

APPENDIX F


Schematic of Biodiesel Production Path
Vegetable Oil/
Animal Fat/Waste
Methanol
plus Catalyst
Transesterification
Crude
Biodiesel
Refining
Biodiesel
Crude Glycerin
Methanol
Recovery
Glycerine
Refining
Glycerin