CHAPTER 1: INTRODUCTION

Abundant and economical energy are the life blood of modern civilizations. However, the global energy consumption is growing faster than the increase in the population. The fuel consumption increased from 6,630 million tons of oil equivalent (Mtoe) in 1980 to 12,274 Mtoe in 2011 (British Petroleum, 2012). It is forecasted by International Energy Agency that the global energy consumption would increase 53% by 2030. The energy consumption is mainly based on fossil fuels which account for 88.1% of the world total primary energy consumption. However the share of nuclear energy and hydroelectricity are very small with only 5.5% and 6.4% respectively. Based on the current production rate, it is estimated that the global proven crude oil and natural gas resources would last for another 41.8 and 60.3 years respectively. Thus, the alternative renewable and sustainable energy has become more important in recent years.

The fossil fuels have significantly contributed to emission production and the climate change. Carbon dioxide (CO_2), nitrogen oxide (NO), volatile organic compounds (VOC) and hydrocarbons (HC) are the main air pollutants which are resulted from the fossil fuels combustion. The major contributor of the greenhouse gas is CO_2 emission and the trend has increased dramatically every year. Huge accumulation of those gases in our atmosphere will eventually lead to drastic climate changes, acid rain and smog. It is predicted that CO_2 will boost up to 40 thousand billion kg in 2030 if no significant efforts are thrown in to alleviate it (Lim and Teong, 2010). Since the main source of the CO_2 emissions are produced from fossil fuels, substituting the fossil fuels with alternative energy resources can reduce the harmful emissions. Therefore, the greenhouse gas mitigation strategies are taken into consideration in recent efforts on the development of global environmental issues, research and urban planning.

Considering the share of the conventional fuels and the contribution in greenhouse gas (GHG) emissions, the development of renewable energies will be taken into account as alternatives energy resources. Currently, 13.3% of the total global energy usage are supplied by renewable energies (International Energy Agency, 2011); and is less significant for transport fuels.

1.1 Background

Transportation sector is one of the major components of globalization and has a vital contribution to the economy (Pucher et al., 2005). Besides, it plays a curial role in daily activities around the world. Although the transport sector is growing quickly and providing benefits such as quick access to any geographical location, it has caused serious negative impact to the environment. Thus, transportation with relatively high energy consumption among the other sectors can be considered as a potential sector to reduce the environmental pollution. (Cervero and Golub, 2007; Hensher, 2008). The generated greenhouse gas and especially the CO_2 emissions by the transportation sector and their rapid growth rates have caused much concern among the community worldwide. At the moment, the transportation sector accounts for 13.5% of global warming (Simoes and Schaeffer, 2005). The amount of CO_2 emitted from distance travelled is directly proportional to fuel economy. For example, with every litre of gasoline burned, it releases about 2.4 kg of CO_2 (Mahlia et al., 2010). Indeed, transportation has the fastest growing carbon emissions compared to other sectors.

The world is confronted with the twin crises of fossil fuel depletion and environmental degradation (Agarwal, 2007). Thus, it is essential to find an alternative renewable energy source that is clean, reliable and yet economically feasible. Biofuel are becoming an increasingly important alternative fuel for transportation sector driven by the factors like oil price spikes, increasing energy security, greenhouse gas emissions from fossil fuels and government subsidies. Biofuel is a renewable energy source produced from natural materials which can be used as a substitute for petroleum fuels. Biofuel can be divided into two main categories which are bioethanol and biodiesel. The bioethanol is compatible with gasoline engines while the biodiesel is compatible with fossil diesel engines (Demirbas, 2009a).

Bioethanol is an alcohol product fermented from organic matter of biological origin that has sugars content (Escobar et al., 2009). Starch-based feedstock and sugar-based feedstock can be considered as two basic categories of feedstock that can be used for bioethanol production. It can be pointed out that corn, grain, wheat, barley and grain sorghum are the raw materials which contain starch convertible into sugar. On the other hand, sugarcane, sugar beets, fruits, citrus molasses and cane sorghum can be named as sugar-based feedstock. Bioethanol as an alternative fuel for gasoline engine vehicles is widely used in USA and Brazil.

Through the transesterification process of the vegetable oils, animal fats or recycled greases can be converted into biodiesel. It is a clean and renewable fuel which is suitable as the alternative fuel for fossil diesel. To denote the importance of applying biodiesel, it can be mentioned that biodiesel is applicable in any compression ignition engine without any modification on the engine and hence slowing down the negative environmental impact of fossil diesel consequently (Fontaras et al., 2009; Frey and Kim, 2009; Chen et al., 2010; Kalam et al., 2011). Therefore, many researches have been conducted on developing biodiesel as a potential energy source for automobile fuels (Reijnders and Huijbregts, 2008; Husnawan et al., 2009; Janaun and Ellis, 2010; Jayed et al., 2011). Biodiesel industry is still in its infancy but is growing rapidly. The world total biodiesel production in 2007 was reported to be 8.4 million toe which increased to 20 million toe in 2010 and it is predicted to reach 150 million toe by 2020 (Agra CEAS Consulting, 2010). However, variability in the feedstock, fossil fuel price and the demand of biodiesel have given rise to instability within the industry (Sotoft et al., 2010). These factors have influenced the economic viability of biodiesel at a global scale.

Malaysia had initiated the development of biodiesel using transesterification technology used on special engines from the early 1980s. The national policy of Malaysia is largely based on palm oil. Hence, development of biodiesel had been growing very quickly in this country. Biodiesel status was further solidified when a mixture of 5% blend of processed palm oil with 95% fossil diesel was introduced in 2006 by Envo Diesel and the implementation of biodiesel usage in the diesel engine by 2010 (Lim and Teong, 2010). However, the volatile price of palm oil has impeded the implementation of palm based biodiesel. From an economic viewpoint, the failure to materialize B5 biodiesel is due to the decision to only focus on one feedstock and this shows a lack of foresight and planning (Goh and Lee, 2010).

Currently, 95% of the world biodiesel production is from edible oil that is easily available on a large scale from the agricultural industry. Since there is a competition between the food and fuel market, this makes edible oil not an ideal feedstock for biodiesel production (Gui et al., 2008; Tan et al., 2009a). Therefore, much focus is shifted to non-edible seeds like *jatropha curcas, pongamia pinnata, calophyllum inophyllum* and etc as feasible feedstock for biodiesel production.

1.2 Problem statement

Malaysia as one of the biggest producers of biodiesel fuel has started the development of biodiesel from palm oil since the 1980s. However, the commercialization and utilization of biodiesel as transportation fuel has not been fully undertaken on a large scale in this country. Besides the technical factors, there are several non-technical limiting factors such as feedstock price, biodiesel production cost, crude oil price, issue of food and fuel, limited land available as well as policy issue such as taxation and subsidy which slow down the development of biodiesel (Enguidanos et al., 2002). The major obstacle in commercializing biodiesel is the high economic cost of production compared to fossil fuel (Yusuf et al., 2011). Among these factors, no matter how much biodiesel production processes are improved, the feedstock cost is still major component of production costs.

A wide variety of biodiesel research on transesterification, performance and emission analysis are currently available worldwide including Malaysia. However, the study on techno-economic analysis and investigating the feasibility of biodiesel fuel in Malaysia are still very limited and not widely recognized yet. There are many criteria which are important to develop and utilize biodiesel fuel as transportation fuel like environmental concern, economic impact, fossil fuel and feedstock price, cropland for feedstock plantation, policy and subsidy cost. These criteria are different for each country and cannot be used as "one size fits all" basis. Therefore, this study focuses on the techno-economic analysis and feasibility of biodiesel as biofuel for road transport in Malaysia.

1.3 Objectives of the study

The primary objective of this study is to assess the biodiesel production and the economic feasibility of applying palm, *jatropha curcas* and *calophyllum inophyllum* as biofuel in Malaysia. The first step to develop effective policies for road transport is to figure out the amount of energy consumption and the emissions produced. Thus, the next objective is to analyse the energy trend and emission pattern for road transport in Malaysia. Moreover, the study continues with proposals and investigations on the biodiesel production process from crude palm, *jatropha curcas* and *calophyllum inophyllum* oil.

There are insufficient studies conducted on the techno-economic analysis and feasibility of biodiesel fuel in Malaysia. Therefore, this study also focuses on developing the life cycle cost model and engineering economic analysis of biodiesel production. The engineering economic analyses carried out in this study are the payback period and sensitivity analysis. After that, the comparison of techno-economic analysis among palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel fuel is also formulated.

Biodiesel fuels help to reduce the diesel fuel consumption and emission in the transportation sector. As such, the study analyzes the effect of replacing the diesel fuel with biodiesel fuel in Malaysia. Those effects include potential energy saving, emission reduction and economic impact when utilised biodiesel fuel in road transport. Besides, the potential taxation and subsidy cost for substituting biodiesel will be discussed. The objectives of the study can be summarized as follows:

- To analyze the energy trend and emission pattern by COPERT model for road transport in Malaysia.
- To propose the use of biodiesel and the implementation of biodiesel policy in Malaysia.
- To investigate and carry out the experiment on biodiesel production process and fuel characteristics study for palm, *jatropha curcas* and *calophyllum inophyllum* oil biodiesel.
- To develop the life cycle cost model and engineering economic analysis of biodiesel production and comparison analysis among palm, *jatropha curcas* and *calophyllum inophyllum* for biodiesel fuel.
- To analyze potential energy saving, emission reduction and economic impact by implementing biodiesel fuel in road transport.

1.4 Contribution of the study

The original contribution of this study is the techno-economic and engineering economic analysis of biodiesel fuel which includes investigating the trends of transportation in Malaysia, developing life cycle cost and payback period analysis, analysing potential energy saving, emission reduction, economic impact such as taxation and subsidy cost by replacing diesel fuel with biodiesel.

This study offers better understanding of techno-economic and feasibility study of biodiesel fuel implementation in Malaysia. As such, it contributed greatly on the areas of energy saving and environmental emission reduction as well as the economic impact of using biodiesel. Although three biodiesels feedstock are investigated in the study, the presented methodology can be applied to other potential feedstock in the future study with minor modification to the developed model.

Finally, the summary for contributions of the research is as follow:

- Propose a method to produce biofuel and implementing biodiesel policy in Malaysia.
- Explore the palm, *jatropha curcas* and *calophyllum inophyllum* production as biodiesel fuel and investigate their characteristics.
- Develop the life cycle cost model and engineering economic analysis for biodiesel production and comparison analysis.
- Predict the potential energy saving and emission reduction by biodiesel fuel in road transport.
- Calculate the potential saving and subsidy cost for the implementation of biodiesel in Malaysia.
- Present a guideline for further investigation on implementation of non-edible biodiesel as transportation fuel.

There are a number of research papers which have been published in the international journal and conference proceedings for the outcome of this study. The list of published papers is presented in Appendix A.

This study has been presented for discussion with policymakers, practitioners and researchers in several conferences and seminars in national and international conference. Besides, this work has also been discussed and referred by the Japanese Automobile Research Institute (JARI) research members on 30 Nov 2011 in University of Malaya. In short, this study seems to be widely accepted by researchers, policymakers and practitioners.

1.5 Thesis Outline

The thesis presents the techno-economic analysis of biodiesel production from palm, *jatropha curcas* and *calophyllum inophyllum* oil as biofuel in Malaysia. The thesis is divided into five chapters and the organization of the thesis is as shown below.

Chapter 1 is an introduction to the research background, problem statement, objectives, contribution of study and thesis outline.

Chapter 2 presents a literature review that consist an overview of related studies regarding transportation energy and biodiesel fuel. A comprehensive review is done to examine its relations with this study. The related areas reviewed include journal articles, conference papers, research reports and etc.

Chapter 3 is the research methodology that consist biodiesel production process, life cycle cost model development, method to conduct engineering and economic analysis, method to calculate energy and environmental impact on biodiesel fuel substitution, method to analyze the taxation, cost saving and subsidy cost with the implementation of the biodiesel fuel.

Chapter 4 covers the results and discussion from the research methodologies done. The results and discussion include the biodiesel production, life cycle cost and payback period for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel production, the potential energy saving, emission reduction and the economic impact of implementing biodiesel fuel. Besides, the cost saving and subsidy cost required for the implementation of the biodiesel fuel are also discussed here.

Chapter 5 is the conclusion of the study which consist the conclusion of the present work and recommendation for future work. In addition, the conclusion achieved in this study is summarized in this section.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The increasing industrialization, modernization and development have led to a high demand for petroleum worldwide. Global final energy consumption grew from 4,676 Mtoe in 1973 to 8,676 Mtoe in 2008 as shown in Table 2.1 (International Energy Agency, 2012). Transportation sector occupied 1,081 Mtoe (23.1%) of energy consumption in 1973 and rose significantly to 2,370 Mtoe which was 27.3% of the total global energy consumption in 2010. The main reason for the increase in transport sector is due to the continuing growth in household incomes and number of vehicles (Hensher, 2008). On the other hand, the world reserves for fossil fuels has been depleting and causing the price to hit new highest record of US$136/barrel in July 2008 (Energy Information Administration, 2010). Therefore, crude oil is mainly used as a backup supply for emergency applications nowadays (Oh et al., 2010). Currently, the world energy consumption is being derived from conventional sources like petroleum, coal and natural gas. In 2011, the combination of energy sources was mainly based on fossil fuels accounting for 87.1% whereby crude oil owned a share of 33.1%, coal 23.7% and natural gas 30.3% as shown in Figure 2.1 (British Petroleum, 2012).

Table 2.1: Global final energy consumption by sector.

Sector	1973		2010	
	Mtoe	Share (%)	Mtoe	Share (%)
Industry	1,544.6	33.0	2,422.9	27.9
Transport	1,081.2	23.1	2,369.8	27.3
Agricultural/commerce/civil	1,764.6	37.7	3,086.5	35.6
Non-energy use	285.3	6.1	797.4	9.2
Total	4,675.7	100.0	8,676.6	100.0

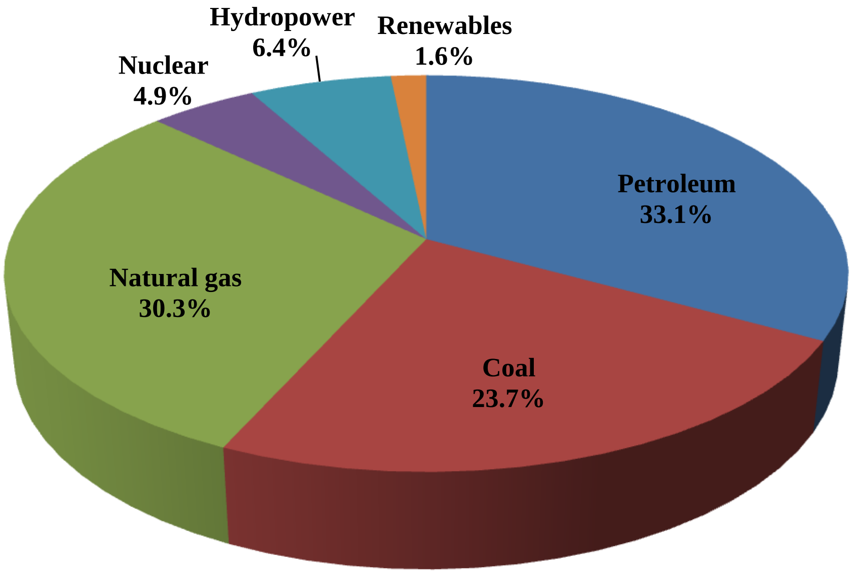

Figure 2.1: World primary energy consumption by sources in 2011.

Global CO_2 emissions increased from 21,000 billion kg in 1990 to 29,400 billion kg in 2010. Within the total world emissions, 41.7% originated from China and the United States, as these two countries alone produced 12,627 billion kg of CO_2 in 2010. On top of that, transportation sector contributed 6,755 billion kg of CO_2 equivalent which is 22.3% of total CO_2 emissions in 2010 as shown in Table 2.2 (International Energy Agency, 2010). It remains the second biggest emitting sector over the period. Table 2.2

shows the CO_2 emission for few selected regions and countries. Figure 2.2 also shows emission trends for different models of transportation system (Energy Information Administration, 2009). Global demand for transport appears unlikely to decrease in the foreseeable future as the World Energy Outlook projected that it will grow 45% by 2030 (International Energy Agency, 2009). Policy makers should first and foremost consider measures to encourage or require improved vehicle efficiency to limit the emissions from this sector. Therefore, in order to utilize the energy consumption and emission reduction for transportation, it is important to analyse the energy pattern of transportation sector.

Table 2.2: Global CO_2 emission by major region and sector in 2010 (billion kg).

Regions	CO_2 emission by sector					Total CO_2
	Electricity	Industry	Transport	Other[1]	Residential	
China	3,576.9 (49.3)[2]	2,333.4 (32.1)	513.6 (7.1)	531.5 (7.3)	303.1 (4.2)	7,258.5
USA	2,309.7 (43.0)	587.1 (10.9)	1,621.7 (30.2)	528.4 (9.8)	321.7 (6.0)	5,368.6
North America	2,424.2 (45.2)	687.9 (12.8)	1,791.4 (33.4)	641.2 (11.9)	360.6 (6.7)	5,905.3
Europe	1,006.6 (32.9)	467.9 (15.3)	811.4 (26.5)	376.2 (12.3)	394.6 (12.9)	3,056.6
OECD	4,937.9 (39.7)	1,754.1 (14.1)	3,325.8 (26.7)	1,440.6 (11.6)	982.0 (7.9)	12,440.3
World	12,480.6 (41.2)	6,186.4 (20.4)	6,755.8 (22.3)	2,973.0 (9.8)	1,880.4 (6.2)	30,276.1

[1]Other includes commercial, agriculture and other emissions not specified elsewhere.
[2]Value inside the parenthesis is in (%)

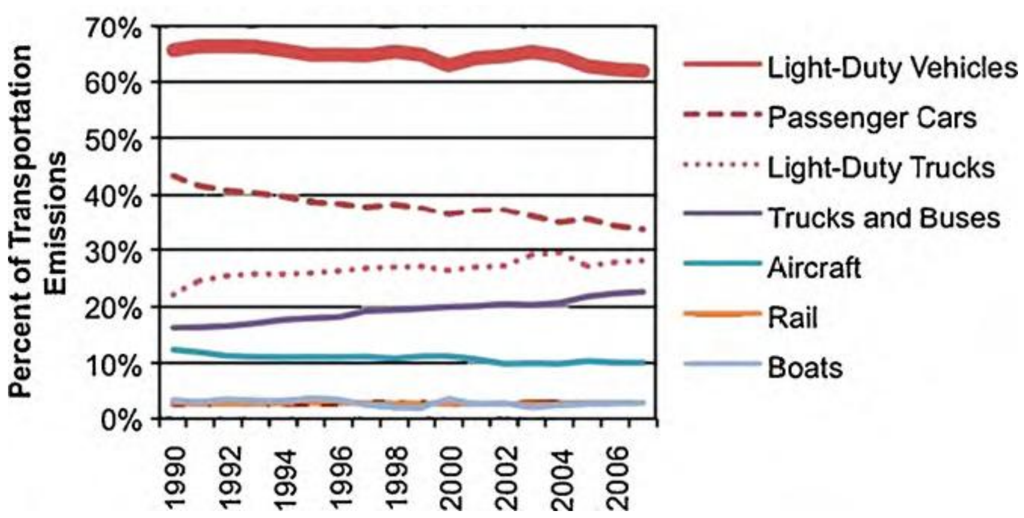

Figure 2.2: CO_2 emissions from transportation sector by mode (Energy Information Administration, 2009).

2.2 Malaysia's energy scenario

Based on the latest census in 2010, Malaysia has a population of about 27.57 million covering an area of 329,750 km^2. The GDP has grown at an average rate over 5.7% in Malaysia during the last 6 years. As such, being a fast industrializing country, it is predicted that energy demand will continue to increase and keep up with the trend of GDP growth. Like many countries, development and economic growth continue to affect the growth of energy consumption demand in the nation. Total primary energy supply has increased steadily over the past 18 years. It was estimated to reach about 64 Mtoe in 2008 (more than 200% increase from 1990) as shown in Figure 2.3 (Malaysian Energy Centre, 2011). This is considered relatively high among developing countries. Apart from that, the amount of final energy consumption has also increased drastically due to rapid urbanization and industrialization. Hence, the final fuel consumption has risen at an annual growth rate of 6.2% from 1990 to 2010 and reached 41.9 Mtoe in 2010. Figure 2.4 shows the final energy consumption by sector from 1990 to 2010 in Malaysia. It also indicates that industrial sector is the major energy consumption with a record of 12.9 Mtoe in 2010 and followed closely by transportation sector which is mostly powered by petroleum products (Malaysian Energy Centre, 2011). It is expected that the energy demand is growing at an annual growth rate of 5-7.9% for the next 20 years (Oh and Chua, 2010). Therefore, energy security is becoming a serious issue as it is highly dependent on non-renewable fossil fuels energy that will be depleted eventually in near future.

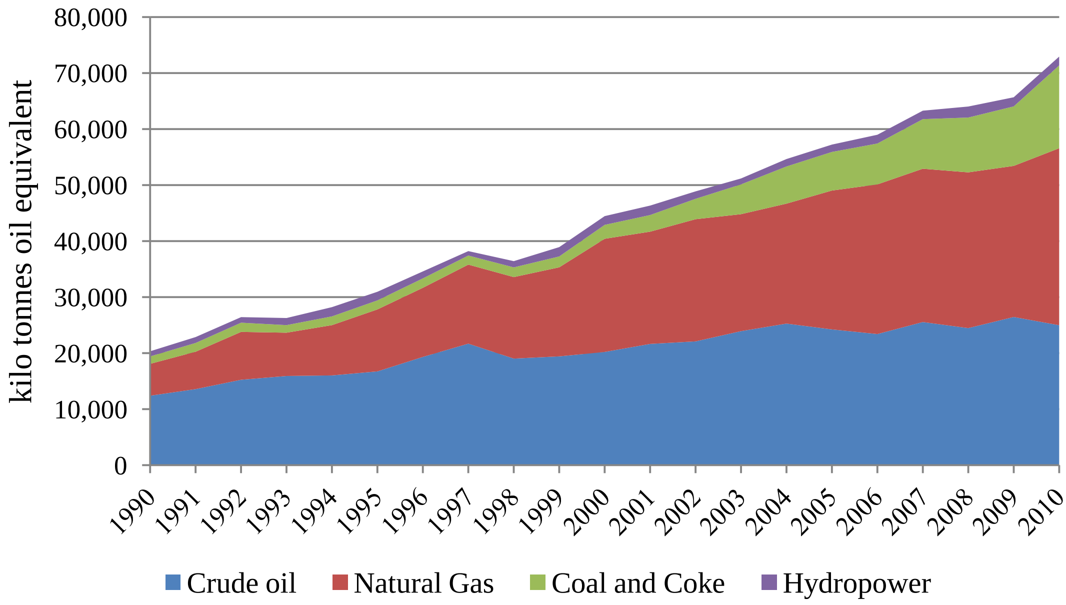

Figure 2.3: Primary energy supply by fuel type in Malaysia.

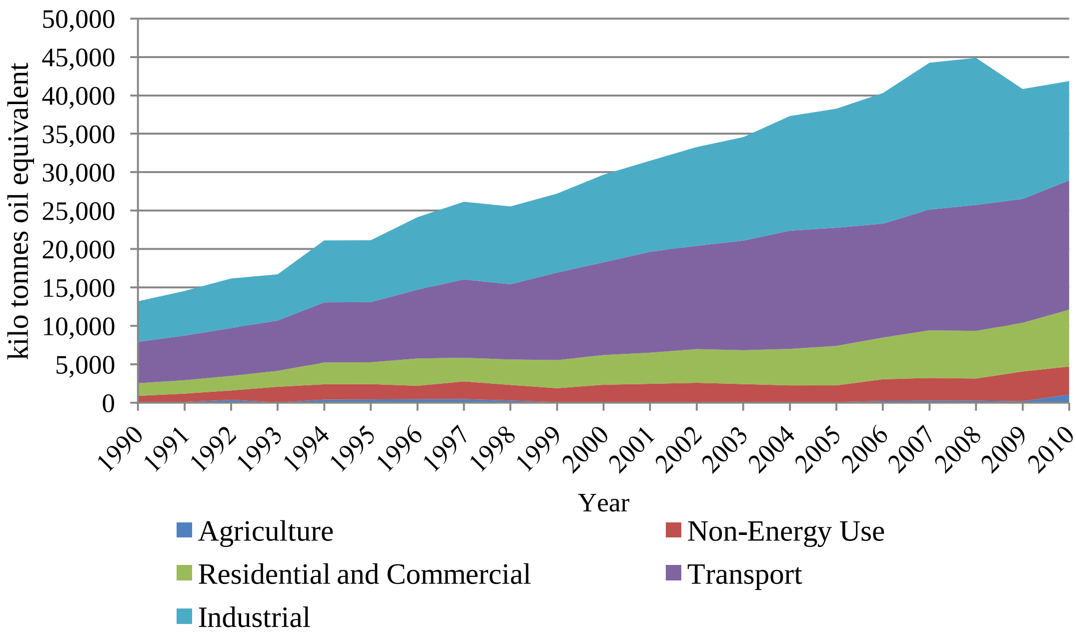

Figure 2.4: Final energy consumption by sector in Malaysia.

Malaysian energy sector is highly dependent on a single source of energy (fossil oil) before 1980. The four fuel diversification policy was introduced and implemented after two international oil crisis occur as well as significant surges in prices were observed in 1973 and 1979 (Mohamed and Lee, 2006). In order to resolve the issue of energy crisis, the government decided to utilize the energy diversification other than crude fossil oil. Malaysian National Energy Policy was established under the fuel diversification strategy so that more balanced energy consumption can be realized (Jafar et al., 2008). Coal, natural gas and hydropower were the alternative energy resources available at that time due to the large untapped indigenous natural gas and hydropower reserves, while coal was considered an abundant worldwide resource with a very low and stable price (Thaddeus, 2002). Table 2.3 shows that the contribution of crude oil in energy supply fell from 61.1% in 1990 to 34.3% in 2010 after the implementation of fuel diversification strategy. Natural gas has become the main contributor of final energy consumption with 43.3% of total energy supply in 2010. The primary energy supply were natural gas 43.3%, crude oil 34.3%, coal 20.3% and hydropower 2.2%. In 2008, Malaysia had proven oil reserves of 5.46 billion barrels and 68% were located in East Malaysia of Sabah and Sarawak (Malaysian Energy Centre, 2011). Malaysia’s crude oil production has declined in recent years and the average oil production were around 690 thousand barrels per day in 2008. When the production rate is consistent at around 700 thousand barrels per day, the ratio between reserve and production of 21 indicated that Malaysia’s oil reserves would be exhausted in next 21 years. Crude oil is no longer considered as a feasible source of energy supply due to its fast depleting supply. Crude oil and natural gas still dominated the energy supply in Malaysia and are expected to continue to play a major role in primary energy mix. However, burning fossil fuels like crude oil and natural gas may totally exhaust in one day. Besides, it leads to the climate change issue and significantly contributes to greenhouse gas emissions. These two issues are main concerns for environmentalists due to the serious effects that might have on the socio-economic development process in Malaysia.

Table 2.3: Primary energy supply in Malaysia.

Primary energy supply	Amount (ktoe)		Share (%)	
	1990	2010	1990	2010
Crude oil	12,434	25,008	61.1	34.3
Natural gas	5,690	31,589	27.9	43.3
Coal and coke	1,326	14,777	6.5	20.3
Hydropower	915	1,577	4.5	2.2
Total	20,365	72,951	100.0	100.0

Malaysia energy sector is highly dependent on non-renewable energy sources such as fossil oil, natural gas and coal. Economic growth in Malaysia depends on the energy consumption which the increase in energy consumption is predicted to be in uptrend around 6-8% annually based on the nation's economic growth. These non-renewable fuels are gradually depleting and contribute to huge amount of greenhouse gas emission. However, Malaysia is not prepared enough to embrace and displace non-renewable energy with renewable energy in the near future. Malaysia has the capability of being a major contributor of renewable energy via palm oil biomass. Subsequently, this country is able to change into a role model for other countries with huge biomass feedstock. This requires a more proactive step taken by government, non-government agencies and the public to promote the renewable energy sources in order to augment the exploitation of these sustainable resources.

2.3 Energy pattern of transportation sector in Malaysia

In Malaysia, the final energy use has risen at an annual growth rate of 6% from year 2000 to 2010 and reached 42 Mtoe in 2010. A significant portion of total energy is consumed in industrial and transportation sector. The transportation sector alone accounted for 36% of total energy consumption in 2008 as presented in Figure 2.5 (Malaysian Energy Centre, 2011). The increase of energy used has raised the concerns of Malaysian government to promote the end-use energy efficiency in order to overcome the excessive energy consumption. Furthermore, transportation sector is highly dependent on petroleum products as the source of energy. Figure 2.6 shows the energy consumption for transportation sector by fuel type. Diesel and petrol are two main fuels used in transportation which are account more than 80% of total consumption. In order to reduce huge demand of fossil fuel in transportation sector, the Malaysian government introduced National Biofuel Policy in 2006. Hence, the government's focus is to improve the energy efficiency as well as sufficiency by utilization of biofuel and biodiesel which will lead to a decrease in the dependency of petroleum products (Jayed et al., 2011).

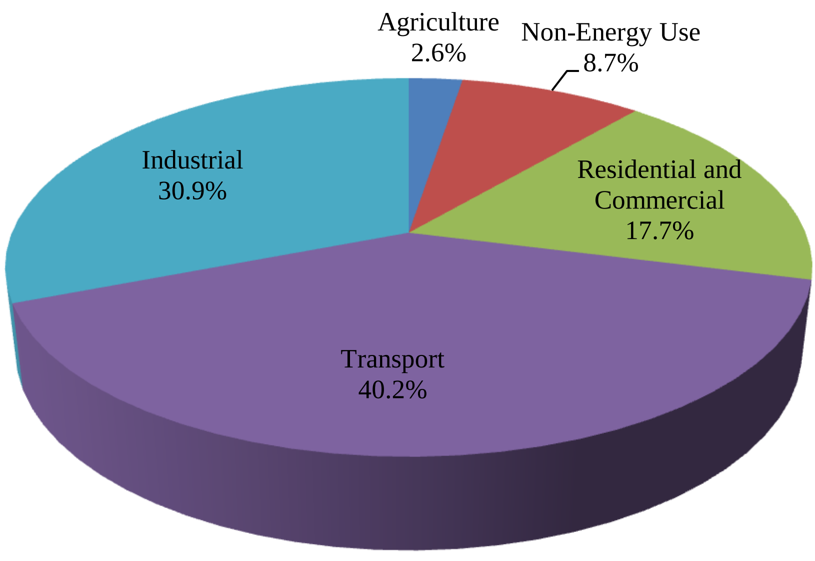

Figure 2.5: Final energy consumption by sector in 2010.

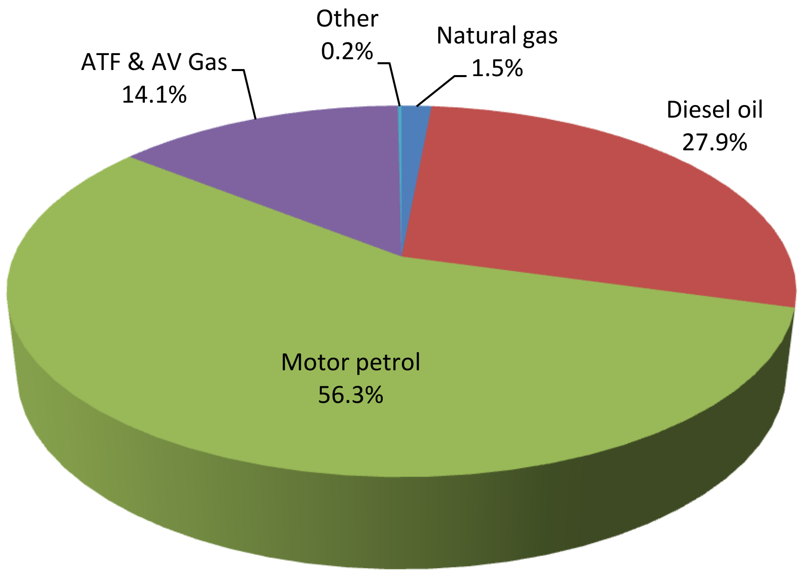

Figure 2.6: Energy consumption for transportation sector by fuel type in 2010.

Despite the benefits of door-to-door transportation and comforts for our daily lives, road transport has the disadvantage of high fuel consumption and significant emissions per km travelled (Soylu, 2007). The road transport emissions have caused serious threats to global warming and urban air quality (Saija and Romano, 2002). Besides, the shortage of fossil petrol and diesel for road transport in near future is another challenge to overcome.

One of the ways to measure the fuel economy for transportation is the fuel consumed in kilometres per litre (km/l) for a distance travelled. The average annual fuel economy ratio for road transport is shown in Figure 2.7. The fuel economy ratio is between 7 and 7.7 km/l from year 1987 to 1999, and the ratio increased steadily after year 1999 to 9.67 km/l in 2008 (Aizura et al., 2010). This increase is due to the technological advances in improving the fuel economy of motor vehicles.

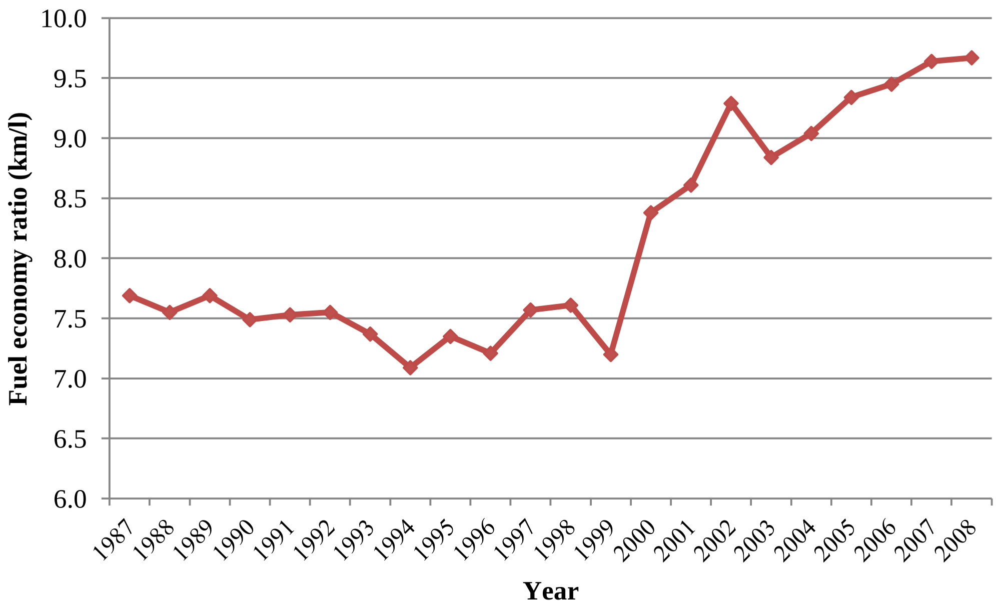

Figure 2.7: Fuel economy ratio for road transport in Malaysia (Aizura et al., 2010).

2.3.1 Energy consumption by transportation sector

Being one of the fast industrialized and boosting of the economy countries, transportation plays a curial role to the economy and makes a vital contribution in daily activities. This is one of the factors that increase energy consumption of the transportation sector. The pattern of energy consumption by transportation sector based on fuel types in Malaysia is illustrated in Figure 2.8 (Malaysian Energy Centre, 2011). Total energy use by transportation sector increased from 7.83 Mtoe in 1995 to 16.8 Mtoe in 2010. This high growth rate is more than double with an annual growth rate of 5.4% over the year. The petrol gasoline, diesel, aviation turbine fuel (AVF), aviation gasoline (AV gas), fuel oil, natural gas and electricity are the main applied fuel types in the Malaysian transportation sector. The main energy sources are fossil fuels in which the primary usage belongs to petrol, followed by diesel and ATF & AV gas. There are some changes in the pattern of energy use after year 2000 whereby the amount of natural gas increased to 247 ktoe in 2010. This is due to the government's policy in promoting natural gas as an alternative fuel for road transport.

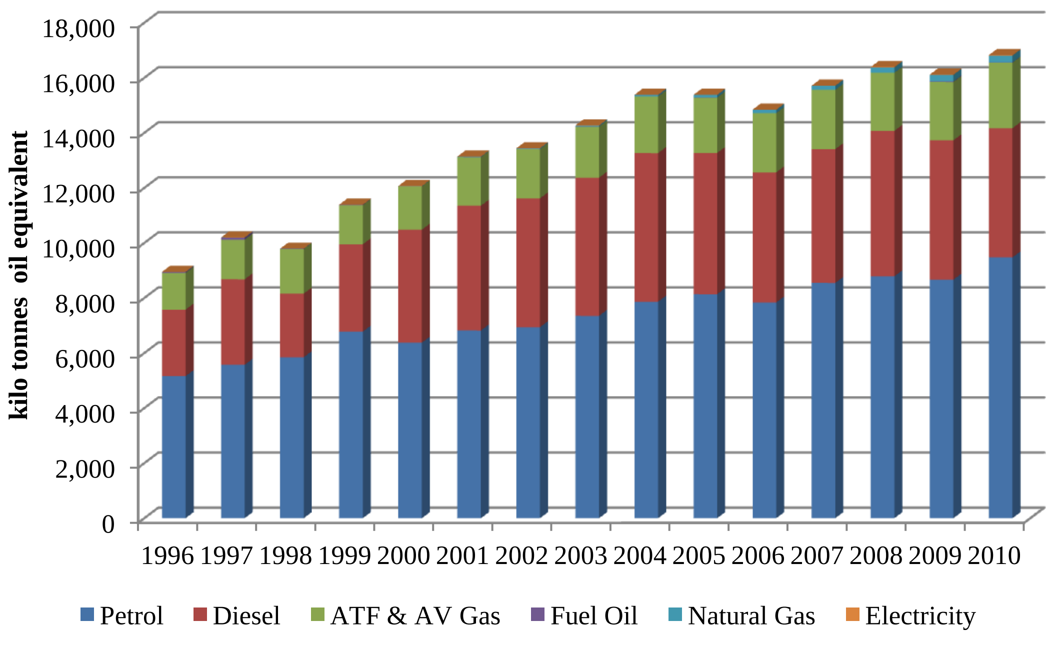

Figure 2.8: Energy use pattern of transportation sector by fuel types.

2.3.2 Mode of transportation

There are few different modes of transportation such as road, rail, air and maritime. Each mode of transport has its own advantages, whereas road transport is a dominant mode of the transportation system. In terms of the number of passenger and the carried freight, road transport is still leading among the other modes of transportation in Malaysia. The proportion of passenger and freight by transportation type are illustrated in Figure 2.9 and Figure 2.10 respectively (Public works department, 2009). There are more than 94% of passengers and 96% of cargo carried by road transport. The rail passenger is about 4.7% while air transport served only 0.5% of total passengers. However, the carried cargo by maritime, rail and air transport were 2.3%, 1.2% and 0.1% respectively.

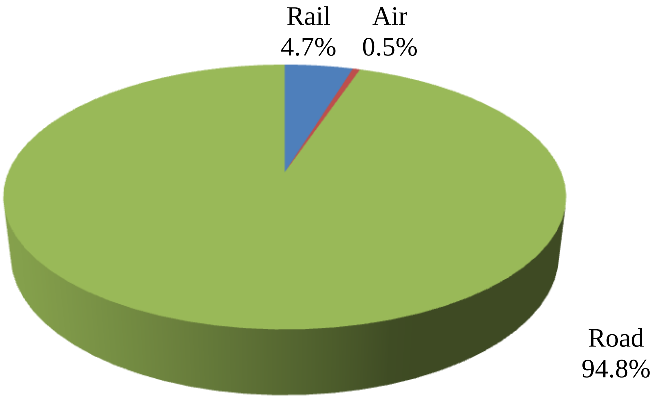

Figure 2.9: Proportion of passenger by transportation type.

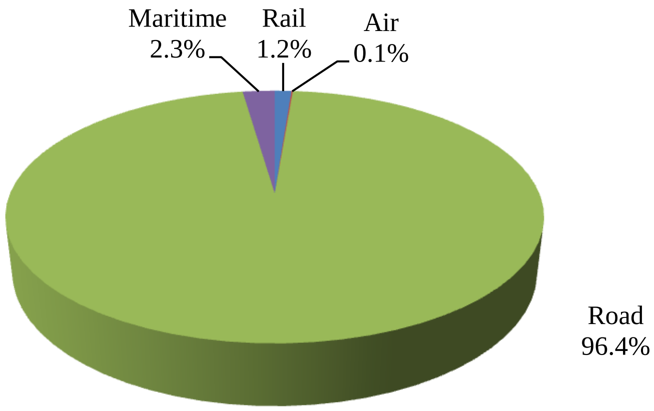

Figure 2.10: Proportion of freight by transportation type.

2.3.3 Transportation fleet pattern

The motor vehicle ownership has increased significantly every year and the number is doubled every 10 years. Table 2.4 shows the road transport vehicles in Malaysia (Department of Road Transport, 2011). The road transport vehicles have increased dramatically from 4.5 million vehicles in 1990 to 18 million vehicles in 2008 which has grown almost 4 times with the annual growth rate of 8%. The highest growth rate was in year 1996 and 1997 with 11.43% and 11.25% respectively. Apart from that, the total vehicle motorization rates have been increasing steadily from 260 in year 1990 to 660 in 2008 per 1,000 populations.

Table 2.4: Road transport vehicles in Malaysia (Department of Road Transport, 2011).

year	**Motorcycles**	**Passenger Cars**	**Buses**	**Taxi/ hire cars**	**Goods vehicles**	**Others**	**Total**	**Growth rate (%)**
1990	2,388,477	1,678,980	24,057	35,405	288,479	132,016	4,547,414	9.44
1991	2,595,749	1,824,679	26,147	38,477	313,514	143,472	4,942,038	8.68
1992	2,762,666	1,942,016	27,827	40,953	333,674	152,698	5,259,834	6.43
1993	2,970,769	2,088,300	29,924	44,040	358,808	164,199	5,656,040	7.53
1994	3,297,474	2,302,547	33,529	47,512	393,833	178,439	6,253,334	10.56
1995	3,608,475	2,553,574	36,000	55,002	440,723	203,660	6,897,434	9.34
1996	3,951,931	2,885,536	38,965	59,456	512,165	237,631	7,685,684	11.43
1997	4,328,997	3,271,304	43,444	62,119	574,622	269,983	8,550,469	11.25
1998	4,692,183	3,452,852	45,643	64,632	599,149	286,898	9,141,357	6.91
1999	5,082,473	3,787,047	47,674	65,646	642,976	304,135	9,929,951	8.63
2000	5,356,604	4,145,982	48,662	66,585	665,284	315,687	10,598,804	6.74
2001	5,609,351	4,557,992	49,771	66,565	689,668	329,198	11,302,545	6.64
2002	5,842,617	5,001,273	51,158	68,139	713,148	345,604	12,021,939	6.36
2003	6,164,958	5,428,774	52,846	70,933	740,462	361,275	12,819,248	6.63
2004	6,572,366	5,911,752	54,997	75,669	772,218	377,835	13,764,837	7.38
2005	7,008,051	6,473,261	57,370	79,130	805,157	393,438	14,816,407	7.64
2006	7,458,128	6,941,996	59,991	82,047	836,579	411,991	15,790,732	6.58
2007	7,943,364	7,419,643	62,308	84,742	871,234	432,652	16,813,943	6.48
2008	8,487,451	7,966,525	64,050	90,474	909,243	454,158	17,971,901	6.89
2009	8,894,571	8,598,244	66,892	95,872	940,987	476,976	19,073,542	6.13
2010	9,441,907	9,114,920	69,149	102,961	966,177	493,451	20,188,565	5.85
2011	9,985,308	9,721,447	71,784	109,214	997,649	515,867	21,401,269	6.01

Public transport is one of the solutions for transportation due to the key player in maintaining congestion at reasonable levels on the roads. Public transport uses the road space more efficiently and consumes less fuel than the passenger car with same passenger-km. However, the average usage of public transport in the city is merely 16% in Malaysia and is the lowest figure among the countries in Asia. Table 2.5 shows the mode split between private and public transport from 1990 to 2011. There is a big difference between the proportion of private car and public transport, whereas the public transport shows a diminishing trend over the year. For example, the proportion of public transport was only 1.83% in 2011 whilst the share of the private passenger car was 98.27%. Public transport is a solution for environmental pollutant and road traffic. Therefore, government should improve and promote the public transport for wider usage to meet the goal of greenhouse gases reduction.

Table 2.5: Proportion trend of private and public transport vehicles for road transport.

year	Private cars		Public transport vehicles		
	Passenger Cars	Share (%)	Buses	Taxi/hire cars	Share (%)
1990	1,678,980	96.58	24,057	35,405	3.42
1991	1,824,679	96.58	26,147	38,477	3.42
1992	1,942,016	96.58	27,827	40,953	3.42
1993	2,088,300	96.58	29,924	44,040	3.42
1994	2,302,547	96.60	33,529	47,512	3.40
1995	2,553,574	96.56	36,000	55,002	3.44
1996	2,885,536	96.70	38,965	59,456	3.30
1997	3,271,304	96.87	43,444	62,119	3.13
1998	3,452,852	96.91	45,643	64,632	3.09
1999	3,787,047	97.09	47,674	65,646	2.91
2000	4,145,982	97.30	48,662	66,585	2.70
2001	4,557,992	97.51	49,771	66,565	2.49
2002	5,001,273	97.67	51,158	68,139	2.33
2003	5,428,774	97.77	52,846	70,933	2.23
2004	5,911,752	97.84	54,997	75,669	2.16
2005	6,473,261	97.93	57,370	79,130	2.07
2006	6,941,996	97.99	59,991	82,047	2.01
2007	7,419,643	98.06	62,308	84,742	1.94
2008	7,966,525	98.10	64,050	90,474	1.90
2009	8,598,244	98.14	66,892	95,872	1.86
2010	9,114,920	98.15	69,149	102,961	1.85
2011	9,721,447	98.27	71,784	109,214	1.83

2.4 Biodiesel

Biodiesel is the renewable energy majorly obtained from vegetable oils or animal fats and has shown great potential to serve as an alternative to fossil diesel in compression ignition (CI) engine (Agarwal, 2007). The world's total biodiesel production was around 1.8 billion litres in 2003 and increased to as high as 20 million toe in 2010 (Lim and Teong, 2010). In European Nations (EU) alone, the demand for biodiesel increased from 3 million tons in 2005 to 10 million tons in 2010 (NBP, 2006). Biodiesel blend fuel is available at many service stations in US and European countries. Besides, Boeing air craft has started its research on using jet biofuel as a sustainable alternative to conventional fuel.

The concept of using biofuel in diesel engines is not a novel idea. An inventor named Rudolph Diesel demonstrated his first developed compression ignition (CI) diesel engine using peanut oil as a fuel at the World Exhibition at Paris in 1900 (Knothe, 2001; Demirbas, 2003). However, the supply of diesel was abundant and vegetable oil fuel had higher price than diesel fuel. As a result, the research and development of vegetable oil to replace diesel was not kept on (Demirbas, 2002). But, there was a renewed interest in vegetable oil in this decade when it was realized that petroleum fuels were depleting fast and environmental friendly renewable substitutes must be identified (Agarwal and Das, 2001). Biodiesel is gradually gaining acceptance as an alternative fuel due to the dwindling of fossil fuel resources and environmental protection reason.

Biodiesel fuel is mono-alkyl ester derived from vegetable or animal and it can be blended with diesel fuel which has characteristics similar to diesel fuel and has lower exhaust emissions (Basha et al., 2009; Foo and Hameed, 2009; Janaun and Ellis, 2010). Typically, vegetable oils comprise 98% of triglycerides and small amounts of mono and diglycerides have the chemical structure as shown in Figure 2.11 (Barnwal and Sharma, 2005). Biodiesel is the process of reacting triglyceride with an alcohol in the presence of a catalyst to produce glycerine and fatty acid esters (Agarwal and Das, 2001).

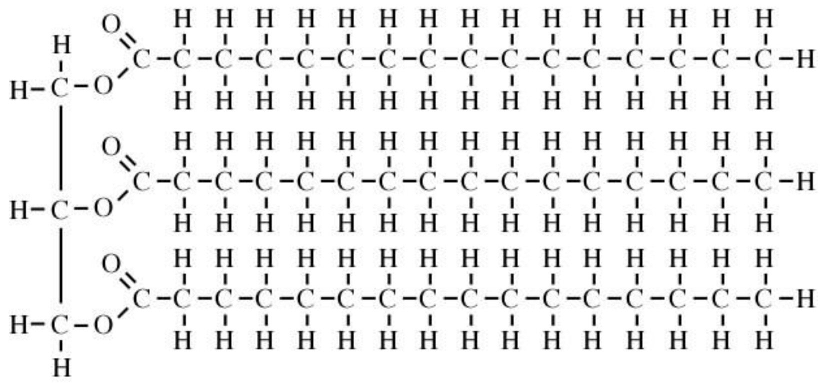

Figure 2.11: Typical structure of a triglyceride molecule (Barnwal and Sharma, 2005).

Vegetable oils contain fatty acid, free fatty acids, phospholipids, phosphatides, carotenes, tocopherols, sulphur compound and traces of water (Singh and Singh, 2010). The fatty acids commonly found in vegetable oils are stearic, palmitic, oleic, linoleic and linolenic. The summary of some common fatty acid composition for vegetable oils is shown in Table 2.6 (Demirbas, 2003; Gui et al., 2008; Sharma et al., 2008; Singh and Singh, 2010). Vegetable oil could be used as engine fuel in different ways such as straight vegetable oil, oil blends, pyrolysis, micro-emulsification and transesterification in diesel engine (Achten et al., 2008).

Table 2.6: Common fatty acids chemical structure for vegetable oil.

Name	Chemical name	Structure (*xx:y*)*	Formula
Lauric	Dodecanoic	12:0	$C_{12}H_{24}O_2$
Myristic	Tetradecanoic	14:0	$C_{14}H_{28}O_2$
Palmitic	Hexadecanoic	16:0	$C_{16}H_{32}O_2$
Stearic	Octadecanoic	18:0	$C_{18}H_{36}O_2$
Oleic	cis-9- Octadecenoic	18:1	$C_{18}H_{34}O_2$
Linoleic	cis-9,cis-12-Octadecadienoic	18:2	$C_{18}H_{32}O_2$
Linolenic	cis-9,cis-l2,cis-15-Octadecatrienoic	18:3	$C_{18}H_{30}O_2$
Arachidic	Eicosanoic	20:0	$C_{20}H_{40}O_2$
Gadoleic	11-eicosenoic	20:1	$C_{20}H_{38}O_2$
Behenic	Docosanoic	22:0	$C_{22}H_{44}O_2$
Erucle	cis-13-Docosenoic	22:1	$C_{22}H_{42}O_2$
Lignoceric	Tetracosanoic	24:0	$C_{24}H_{48}O_2$

**xx:y*, where *xx* = total number of carbon atoms and *y* = number of double bonds

Biodiesel has combustion characteristics similar to diesel fuel. However, biodiesel blends have shorter ignition delay, higher ignition temperature, ignition pressure and peak heat release compared to diesel fuel (Basha et al., 2009). Moreover, the engine power output and brake power efficiency by biodiesel fuel was found to be similar to diesel fuel. Biodiesel and diesel blends can reduce smoke opacity, particulate matters, un-burnt HC, CO_2 and CO emissions but NO emissions would slightly increase (Bozbas, 2008). On the other hand, the main drawback of biodiesel fuels is their high viscosity and low volatility which will cause the poor combustion in diesel engines. Transesterification is the processes employed to decrease the viscosity and enhance the other characteristics of biodiesel (Balat and Balat, 2008). This process reduces the viscosity of the biodiesel fuel to a range 4–5 mm^2/s closer to diesel fuel and hence improves combustion (Sahoo et al., 2009; Knothe, 2010). Biodiesel or fatty acid ester can be considered as an efficient, clean and renewable energy alternative to diesel fuel.

2.4.1 Standard of biodiesel

Generally, biodiesel is defined as a domestic renewable fuel for diesel engines derived from vegetable oils like palm, soybean and rapeseed oil that meet the specifications of EN 14214 or ASTM D 6751. Technical properties of biodiesel are presented in Table 2.7 (Demirbas, 2009b). Biodiesel is a clear amber-yellow liquid with a viscosity similar to fossil diesel fuel.

Table 2.7: Technical properties of biodiesel (Demirbas, 2009b).

Common name	Biodiesel
Common chemical name	Fatty acid (m)ethyl ester
Chemical formula range	C_{14}–C_{24} methyl ester or $C_{15-25}H_{28-48}O_2$
Kinematic viscosity range (mm^2/s, at 40^oC)	3.3–5.2
Density range (kg/m^3, at 15^oC)	860–894
Boiling point range (^oC)	>202
Flash point range (^oC)	147–177
Distillation range (^oC)	200–325
Vapour pressure (mm Hg, at 22 ^oC)	<5
Solubility in water	Insoluble in water
Physical appearance	Light to dark yellow, clear liquid
Odour	Light musty/soapy odour
Biodegradability	More biodegradable than petroleum diesel
Reactivity	Stable but avoid strong oxidizing agents

The biodiesel standard testing materials are American standards ASTM D6751 and European Union standard EN 14214 (Atadashi et al., 2010). American standard ASTM D6751 identifies the characteristics that pure biodiesel (B100) must meet before being used as a pure fuel or blended with diesel fuel. Biodiesel (B100) specifications ASTM D6751 standard is shown in Table 2.8 (Murugesan et al., 2009). However, European Union standard EN 14214 describes the minimum requirements for FAME as summarized in Table 2.9 (Demirbas, 2009b). The quality of biodiesel fuel might be substantially influenced by numerous factors including: the quality of feedstock, fatty acid composition of the vegetable oils, animal fats and waste oils, type of production and refining process employed and post-production treatment.

Table 2.8: ASTM D6751 standard properties for biodiesel (B100) (Murugesan et al., 2009).

Property	ASTM Method	Limits	Units
Flash point	D93	130 min.	^{0}C
Kinematic viscosity, 40^{0}C	D445	1.9–6.0	mm^2/s
Cetane Number	D613	47 min.	-
Cloud point	D2500	Report	^{0}C
Carbon residue 100% sample	D4530	0.050 max.	mass%
Acid number	D664	0.50 max.	mg KOH/g
Sulfated ash	D874	0.020 max.	mass%
Sulfur	D5453	-	-
S15 grade	-	15 max.	ppm
S500 grade	-	500 max.	ppm
Copper strip corrosion	D130	No. 3 max.	-
Free glycerine	D6584	0.020 max.	mass%
Total glycerine	D6584	0.240 max.	mass%
Phosphorus content	D4951	0.001 max.	mass%
Distillation temperature, 90% recovered	D1160	360 max.	^{0}C
Water and sediment	D2709	0.050 max.	vol.%
Sodium/potassium	UOP391	5 max. combined	ppm

Table 2.9: European Union standard (EN 14214) properties for biodiesel (Atadashi et al., 2010).

Property	lower limit	upper limit	Units	Test-Method
Density at 15 ℃	860	900	kg/m ³	EN ISO 3675 / EN ISO 12185
Viscosity at 40 ℃	3.5	5.0	mm ²/s	EN ISO 3104
Flash point	> 101	-	℃	EN CD 3679e
Sulphur content	-	10	mg/kg	-
Tar remnant (at 10% distillation remnant)	-	0.3	% (m/m)	EN ISO 10370
Cetane number	51.0	-	-	EN ISO 5165
Sulfated ash content	-	0.02	% (m/m)	ISO 3987
Water content	-	500	mg/kg	EN ISO 12937
FAME content	96.5	-	% (m/m)	pr EN 14103
Total contamination	-	24	mg/kg	pr EN 12662
Copper band corrosion (3hours at 50 ℃)	Class 1	Class 1	rating	EN ISO 2160
Oxidation stability, 110 ℃	6	-	hours	pr EN 14112k
Acid value	-	0.5	mg KOH/g	pr EN 14104
Iodine value	-	120	mg I_2/g	pr EN 14111
Linoleic Acid Methyl ester	-	12	% (m/m)	pr EN 14103d
Polyunsaturated (≥4 Double bonds) Methyl ester	-	1	% (m/m)	-
Methanol content	-	0.2	% (m/m)	pr EN 14110l
Monoglyceride content	-	0.8	% (m/m)	pr EN 14105m
Diglyceride content	-	0.2	% (m/m)	pr EN 14105m
Triglyceride content	-	0.2	% (m/m)	pr EN 14105m
Free Glycerine	-	0.02	% (m/m)	pr EN 14105m / pr EN 14106
Total Glycerine	-	0.25	% (m/m)	pr EN 14105m
Group I metals (Na+K)	-	5	mg/kg	pr EN 14108 / pr EN 14109
Group II metals (Ca+Mg)	-	5	mg/kg	pr EN 14538
Phosphorus content	-	4	mg/kg	pr EN14107p

2.4.2 Feedstock (raw material) of biodiesel

There are more than 350 oil bearing crops or feedstock identified as potential sources for biodiesel production (Altin et al., 2001; Demirbas, 2008). Production of biodiesel as an alternative energy resource has benefits from an extensive range of available feedstock. The most common raw oils used for biodiesel production are palm, soybean, rapeseed, sunflower, canola and *jatropha*. Due to the competitiveness between food and fuel as well as the higher cost of edible vegetable oils than diesel fuel, waste vegetable oils and non-edible oils are preferred as potential feedstock for biodiesel. Table 2.10 shows main feedstock of biodiesel categorised into vegetables oils, non-edible oils, animal fats and some other biomass.

Table 2.10: List of the biodiesel feedstock (Singh and Singh, 2010).

Vegetable oils	Non-edible oils	Animal Fats	Other Sources
Almond	Abutilon muticum	Fish oil	Algae
Barley	Babassu	Poultry Fat	Bacteria
Canola	Brassica carinata	Tallow	Cooking oil
Coconut	Brassica napus		Fungi
Groundnut	Camelina		Latexes
Palm	Calophyllum inophyllum		Microalgae
Peanut	Cynara cardunculus		
Rapeseed	Jatropha curcas		
Rice	Jojoba oil		
Safflower	Laurel		
Sorghum	Mahua		
Soybeans	Pomace		
Wheat	Pongamia pinnata		
	Rice bran		
	Tobacco seed		

Climate location, geographical regions and the agricultural practices in different parts of the country are the influential factors on the availability of feedstock for biodiesel production. Thus, the selection of the source or feedstock for biodiesel production is depending on the availability of the countries. Rapeseeds are commonly used in European countries for food product and even have surplus amount to export. Therefore, rapeseed (Rashid and Anwar, 2008; Reijnders and Huijbregts, 2008) are used in European Nations for biodiesel production. Besides, soybean biodiesel is the main source of feedstock for biodiesel in United States due to the soybeans (Kinney and Clemente, 2005; Thompson et al., 2010) being the primary food products and have surplus of in the country (Sharma and Singh, 2009). Similar countries with coastal areas such as Malaysia, Indonesia and Thailand have surplus palm oil (Jayed et al., 2009) and coconut oil (Nakpong and Wootthikanokkhan, 2010) which are utilised for the biodiesel production (Ahouissoussi and Wetzstein, 1998). However, some Asian countries that are not self-sufficient in edible oil are exploring the non-edible feedstock for biodiesel fuel. Non-edible oil resources are gaining attention due to easy availability in many countries especially wastelands that are not appropriate for food crops and this helps to eliminate competition between food and fuel. Furthermore, it is more efficient and economical compared to edible oil. *Jatropha curcas* (Openshaw, 2000; Jain and Sharma, 2010) and karanja oil (*pongamia pinnata*) (Naik et al., 2008) are used as significant fuel sources for biodiesel in India and Southeast Asia (Sarin et al., 2007). In Brazil, the mostly used oil source for the biodiesel productions are soybean, castor bean and palm kernel (Chongkhong et al., 2007; Canoira et al., 2010). There are other different feedstock sources mentioned in literature such as sunflower oil (Kalligeros et al., 2003), cotton seed oil (Rashid et al., 2009), pomace oil (Caynak et al., 2009), canola oil (Kulkarni et al., 2007), peanut oil (Kaya et al., 2009) and *calophyllum inophyllum* oil (Sahoo et al., 2009) as potentially suitable oil sources for biodiesel production.

Oil yield and oil percentage are important parameters to consider when selecting a feedstock as a biodiesel source. Palm oil has the potential to become biodiesel feedstock due to its high production rate to satisfy the future energy requirements and has high oil content. Figure 2.12 shows the oil yield of various oil sources for biodiesel feedstock (Karmakar et al., 2010). As observed from the figure, the highest oil productivity belongs to *calophyllum inophyllum* oil which is 5385 litres/ha followed by oil palm. A reduction of 62% in GHG emission by palm oil biodiesel as compared to soybean oil (40%), rapeseed oil (45%) and sunflower oil (58%) is the results obtained via life cycle analysis (LCA) performed on different biodiesels (Sani, 2009).

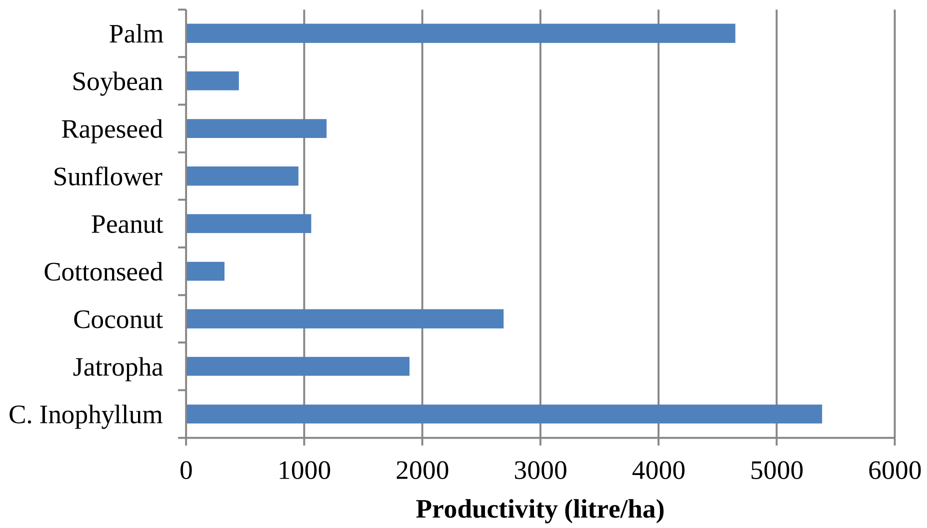

Figure 2.12: Production oil yield for various source of biodiesel feedstock (Karmakar et al., 2010).

2.4.3 Biodiesel trend and policy

The global potential volume of biodiesel production is 51 billion litres annually and top five biodiesel production countries are Malaysia, Indonesia, Argentina, United States and Brazil that account for over 80% of the total production. Table 2.11 shows the top 10 countries ranked in terms of overall biodiesel potential production volume with Malaysia far ahead among the rest. The main feedstock sources of biodiesel production for these countries are soybean oil (28%), palm oil (22%), animal fats (20%), coconut oil (11%) and 5% of rapeseed, sunflower and olive oils each (Johnston and Holloway, 2007). The potential market for biodiesel in road transport is projected to climb from 24 Mtoe in 2006 to 118 Mtoe in 2030 (International Energy Agency, 2009). The rapid increase of biofuel in transportation is due to new national biofuel policy in several countries and high fossil oil price. Most of the growth comes from the United States, Europe, China and Brazil. Currently, ethanol accounts for a larger share of the global biofuel market than biodiesel but the demand for biodiesel is growing faster than ethanol. The European Union and Asia have the fastest growth in demand for biodiesel. Several countries have aggressive policies in place for encouraging the production and use of biodiesel. These countries have adopted policies such as tax exemptions, mandates and incentives for biodiesel utilization. United States and European Union have notably moved to promote more fuel efficient vehicles and encourage biodiesel supply contribution to the GHG reduction. In United States, the Energy Independence and Security Act 2007 mandate a significant increase in biofuel use by 2020. Besides, the European Union has a target for biofuel to meet at 10% of road transport demand by 2020 (International Energy Agency, 2009). Table 2.12 shows the summary of biofuel policies in some selected countries. Most of the Southeast Asian countries including Malaysia have mainly focused on exporting the production of biofuel rather than utilization in their own countries.

Table 2.11: Top 10 countries by absolute biodiesel production (Johnston and Holloway, 2007).

No	Country	Volume (million litres)
1	Malaysia	14,540
2	Indonesia	7,595
3	Argentina	5,255
4	USA	3,212
5	Brazil	2,567
6	Netherlands	2,496
7	Germany	2,024
8	Philippines	1,234
9	Belgium	1,213
10	Spain	1,073

Table 2.12: Summary of biofuel policies in some selected countries (Jayed et al., 2009).

Country	Biofuel policy
Brazil	40% rise in ethanol production, 2005–2010; Mandatory blend of 20–25% anhydrous ethanol with petrol; minimum blending of 3% biodiesel to diesel by July 2008 and 5% (B5) by end of 2010.
Canada	5% renewable content in petrol by 2010 and 2% renewable content in diesel fuel by 2012.
European Union	10% biofuel in 2020 set by European Commission in 2008.
Germany	2% ethanol and 4.4% biodiesel in 2007, increasing to 5.75% by 2010
Indonesia	2% of energy mix by 2010, 3% by 2015 and 5% by 2025. Seriously considering *jatropha* and cassava.
Malaysia	Envo Diesel in all fuel stations and industrial sectors from 2008 (unsuccessful). Implementing the mandatory use of biodiesel for vehicles put off to 2011.
Thailand	5% and 10% replacement of diesel in 2011 and 2012 respectively.
UK	5% biofuel energy content by 2020.
US	Energy Independence and Security Act 2007 mandate a significant increase in biofuel use by 2020.

The use of biodiesel fuel in compressed ignition (CI) engines could effectively reduce the environmental impact of fossil fuels in both developed and developing countries. According to five encouraging strategies, by the aid of national biofuels policy a comprehensive framework would be spelled out and concrete initiatives for the use of biodiesel will be established (Abdullah et al., 2009). This policy is expected to reduce the dependency of petroleum and diesel. At the same time, it is also in line with the global efforts to reduce the greenhouse gasses.

As indicated previously, the national biofuel policy of Malaysia is mainly dependent on palm oil. Malaysia has initiated a comprehensive palm biodiesel program since 1982. Biodiesel's status as a renewable energy source was further solidified in Malaysia when Envo Diesel was introduced through the National Biofuel Policy in 2006 (Lim and Teong, 2010). Envo Diesel was a mixture of 5% blend of palm oil with 95% petroleum derived diesel. However, Malaysian government has stopped the Envo Diesel project as it failed to market in 2008 as planned due to price rise for crude palm oil. Therefore, the government has put off the mandatory implementation of biofuel to 2011. The mandatory biofuel implementation involves 5% of palm methyl ester blended with 95% diesel and is part of the country's biofuel initiative under the B5 program. Apart from that, the biofuel implementation plan includes the RM43.1 million instigation of depot with inline blending facilities to be placed in Port Klang, the Klang Valley Distribution Terminal (KVDT) in Selangor, Negeri Sembilan and Tangga Batu, Malacca. Besides, replanting is widely seen as a way to enhance productivity and also to achieve Malaysia's long-term target at an average of 35 tons of fresh fruit bunches and oil extraction rate of 25% by 2020 (Adnan, 2010). Besides, Malaysia government has enforced Renewable Energy Act 2011.

As a result of the volatile price of palm oil, the implementation of Envo Diesel has been impeded. In years 2006 and 2007, 92 biodiesel projects were approved out of which only 14 have been built since and 8 being operational in 2008 (Lopez and Laan, 2008). The remaining plants have been suspended operation and shut down due to high feedstock prices and failure of Envo Diesel project. The failure to materialize Envo Diesel epitomizes the haphazard planning of the biodiesel industry. This phenomenon reflects the over-optimization of project output. Instead of unrealistic assumptions, more effort should be put on fundamental technology and functionalities. From economical point of view, the decision should not focus on one feedstock only (Goh and Lee, 2010).

2.4.4 Palm oil based biodiesel

The botanical classification of oil palm is *Elaeis guineensis* and native to the West Africa where it was growing wild and later developed into an agricultural crop (Basiron, 2007). *Elaeis guineensis* is the most productive oil palm variety which can produce 10–35 thousand kg/ha of fresh fruit bunch (FFB) oil palm annually (Singh et al., 2010). The oil palm is a tropical perennial plant and grows well in lowland with humid climate which makes it easily cultivable in Malaysia (Lam et al., 2009). The tree which is un-branched and single-stemmed can grow up to 20–30m height (Edem, 2002). The fleshy orange reddish coloured fruits grow in large and tight female bunches with each fruit weigh as much as 10–40 kg containing up to 2000 fruitlets as shown in Figure 2.13 (Sumathi et al., 2008). In Malaysia, the oil palm plantations are planted with a density of 148 palms per hectare. The fruitlet consists of a fibrous mesoscarp layer and the endocarp (shell) has the kernel which contains oil and carbohydrate reserves for the embryo as shown in Figure 2.14 (Guo and Lua, 2001; Foo and Hameed, 2009).

Figure 2.13: Oil palm tree and fruits.

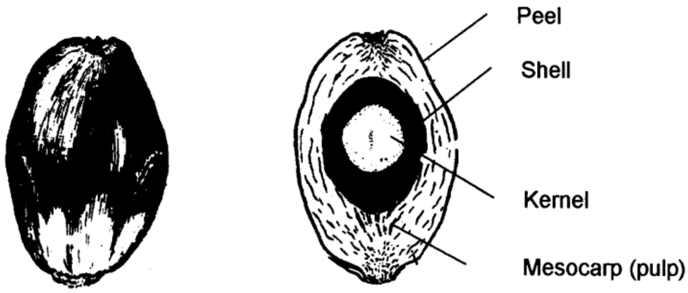

Figure 2.14: Fresh oil palm fruit and its longitudinal section (Guo and Lua, 2001).

Oil palm is high oil yield crop producing on average about 4000–5000 kg/ha annually which is about 10 times and 6 times the yield of soybean and rapeseed oil respectively (Sumathi et al., 2008). There are two main products produced by the oil palm fruit which are crude palm oil and crude palm kernel oil. Crude palm oil is obtained from the mesocarp and kernel oil is obtained from the endosperm (kernel). The mesocarp contains about 49% of palm oil and the kernel about 50% of palm kernel oil. Table 2.13 shows the dry weight composition of fresh ripe fruit and mesocarp for oil palm (Yusoff, 2006).

Table 2.13: The dry weight composition of fresh ripe fruit and mesocarp for oil palm (Yusoff, 2006).

Fruit	Dry weight (%)	Mesocarp	Dry weight (%)
Palm oil	29	Palm oil	46–50
Water	27	Palm oil (dry basis)	77–81
Residue	8	Moisture	36–40
Shell	30	Non-fatty solids	13–15
Kernel	6		

Global need for edible oil has augmented in the last few decades leading to a substantial rise in the area of oil crop cultivation especially soybean and oil palm. The world production of palm oil is 45 million toe and the highest production belongs to South East Asia with 89% of total palm oil production (40% in Malaysia, 46% in Indonesia, 3% in Thailand) as shown in Figure 2.15 (United States Department of Agriculture, 2010b).

Malaysia is the world's second largest producer and exporter of palm oil following Indonesia. In 2010, it produced 17 million tons of palm oil compared to 23 million tons in Indonesia (Malaysian Palm Oil Board, 2010). In Malaysia, 4.5 million hectares of land is allocated to oil palm cultivation. There are approximately 362 palm oil mills, processing 71.3 million tons of fresh fruit bunch per year and producing an estimated annual 19 million tons of crop residue in the form of empty fruit bunch, fibre and shell (Puah and Choo, 2008). A life cycle assessment study has been conducted and the study shows that palm oil biodiesel has huge positive energy yield ratio of 3.53 (output energy/input energy) compared to 1.44 for rapeseed oil (Yee et al., 2009). Considering productivity, efficiency and land utilization, palm oil is considered as one of the most optimum oil bearing crop.

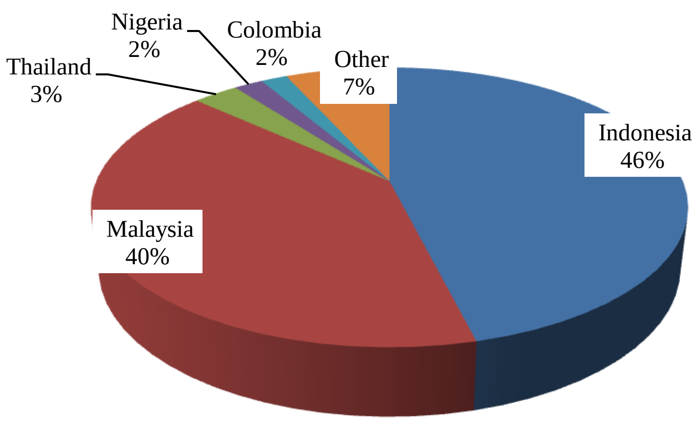

Figure 2.15: World palm oil production in 2009 (United States Department of Agriculture, 2010a).

Although Malaysia is the biggest producer of biodiesel fuel, the commercialization of biodiesel is yet to be performed at a large scale. Besides the technical factors, there are several non-technical limiting factors slowing the development of biodiesel such as feedstock price, biodiesel production cost, crude oil price and taxation (Enguidanos et al., 2002). Among these factors, the feedstock cost is still the major contribution towards the production costs, no matter how the biodiesel production processes is improved.

2.4.5 *Jatropha curcas* biodiesel

Jatropha curcas is a large shrub belonging to the genus *Euphorbiaceae* native in tropical America but widely distributed in tropical and subtropical regions throughout Africa, India and South East Asia (Jongschaap et al., 2007). This is a tropical plant that could be grown as commercial crop in the farms or as hedges on the boundaries of field (in areas with low or high rainfall) (Behera et al., 2010). It can be planted in all sorts of soils and also needs little irrigation. *Jatropha curcas* is well adapted to semi-arid conditions, although more humid environmental conditions result in better crop performance. The *jatropha curcas* plant is drought-resistant and has the capability to grow on marginal soils and on reclaim wasteland (Divakara et al., 2010).

The competition between food and fuels such as palm oil, soybean oil and rapeseed oil makes edibles oil unsuitable sources for biodiesel fuel. In addition, in some countries like India which faces deficiency of edible oil, *jatropha curcas* oil has become the choice for biodiesel. The *jatropha curcas* plant has a long productive period with an effective yield up to 50 years and reaping large return annually. The production of the seeds is about 0.8 kg/m^2 per year (Banapurmath et al., 2008). The oil content of seed ranges from 30–50% by weight and the kernel ranges from 45% to 60% (Pramanik, 2003). The fatty acid composition of *jatropha curcas* is classified as linoleic or oleic acid types which are unsaturated fatty acids. Fresh *jatropha* is a slow drying, odourless and colourless oil and becomes yellow after aging as shown in Figure 2.16. The production of *jatropha* oil soil will give 1600 kg/ha oil on average (Jain and Sharma, 2010). In 2008, *jatropha* cultivation has occupied an estimated 90,000 hectares globally including 85% in Asia and the rest in Africa and Latin America. It is expected that the *jatropha* will be planted on 12.8 million hectares worldwide in 2015 (Kant and Wu, 2011).

Figure 2.16: *Jatropha curcas* plant and seed.

Jatropha curcas oil, a branched triglycerides type of non-edible vegetable oil is a potential alternative diesel fuel. Its methyl ester properties are close to diesel fuel and able to reduce CO_2 in the atmosphere when it is utilized in diesel engine. However, direct burning of *jatropha curcas* oil in diesel engine can lead to numerous problems regarding its viscosity which is around ten times higher than that of diesel. The high viscosity of oils is the consequence of their large molecular weight and chemical structure (Wardana, 2010). Therefore, reducing the viscosity is very important to make *jatropha* oil an appropriate alternative fuel for diesel engines. There are several different methods to reduce the high viscosity which include preheating the oil, micro-emulsion with solvents, dilution with diesel fuel, thermal cracking or pyrolysis and transesterification (Tippayawong et al., 2002; Pramanik, 2003). *Jatropha curcas* particularly owns an additional advantage over other non-edible oil sources because it is a drought-resistant plant that has the capability of surviving in abandoned and fallowed agricultural land (Achten et al., 2008). Consequently, it has attracted much interest to be used as a feedstock due to its certain potentials. In Malaysia, biodiesel produced from *jatropha curcas* oil is still in its nascent state compared to palm oil based biodiesel industry (Jayed et al., 2009).

2.4.6 *Calophyllum inophyllum* biodiesel

Calophyllum Inophyllum, commonly known as Penaga Laut or Bintangor in Malaysia, is a non-edible oilseed ornamental evergreen tree belonging to the *Clusiaceae* family as shown in Figure 2.17 (Friday and Okano, 2006; Moser, 2009). The scientific name of "*Calophyllum*" comes from the Greek word "*beautiful leaf*". It grows along coastal areas and adjacent to lowland forests, although it occasionally grows inland at higher elevations. It is the local product of eastern Africa, southern coastal India, Southeast Asia, Australia and the South Pacific. *Calophyllum inophyllum* is also often called as 'Alexandrian Laurel' in English and other vernacular names in various countries as shown in Table 2.14 (Institute for Medical Research, 2010).

Figure 2.17: Photo of *calophyllum inophyllum* plant and fruit.

Table 2.14: Vernacular names for *calophyllum inophyllum* (Institute for Medical Research, 2010).

Country	Vernacular names
Bangladesh	Punnang
Cambodia	Khtung, Kchyong
English	Alexandrian laurel, Borneo mahogany, Tamanu
Hawaii	Kamani
India	Polanga, Sultan Champa
Indonesia	Nyamplung, Bintangur
Malaysia	Penaga Laut, Bintangor
Myanmar	Ponnyet
Palau	Btaches
Papua New Guinea	Beach calophyllum
Philippines	Butalau, palo maria, bitaog
Thailand	Krathing, saraphee (northern), naowakan (Nan)

Calophyllum inophyllum is a medium and large-sized evergreen sub-maritime tree that averages 8 to 20 m (25 to 65 ft) in height with a broad spreading crown of irregular branches. It has elliptical, shiny and tough leaves. The flower is around 25mm wide and exists in racemose or paniculate inflorescences consisting of 4 to 15 flowers. The fruit (ballnut) is a round, green drupe reaching 2 to 4 cm (0.8 to 1.6 in) in diameter and having a single large seed as shown in Figure 2.18. When it is ripe, the fruit is wrinkled and its colour varies from yellow to brownish-red. The nut is usually soft, grey and ligneous containing a pale yellow kernel and is odourless when fresh. *Calophyllum inophyllum* kernels have very high oil content (75%) and the oil contains approximately 71% of unsaturated fatty acids (essentially oleic and linoloeic acids) (Said et al., 2007).

Fruits are usually borne twice a year producing up to 100 kg of fruits and about 18 kg of oil (Dweck and Meadowsy, 2002). *Calophyllum inophyllum* is grown in warm climates in wet or moderate conditions and requires mean annual rainfall of around 1000–5000 mm (Friday and Okano, 2006). The trees are well resistant to gusts, brackish water tables and salt spray which make this plant appropriate for sand dune stabilization. However, it is sensitive to fire and frost (Sahoo et al., 2007). Plantation can be done at a density of 400 tree/hectare (Azam et al., 2005) with an average oil yield of 11.7 kg/tree or 4680 kg/hectare.

Figure 2.18: *Calophyllum inophyllum* seed and cracked shell showing kernel inside.

Traditional Pacific Islanders used *calophyllum* wood to construct the keel of their canoes while the boat sides were made from breadfruit wood. In Java, the tree is known to possess diuretic properties. The emetic and purgative gum extracted from the plant is used for the treatment of wounds and ulcers. An infusion of gum, bark and leaves is used for sore eyes (Dweck and Meadowsy, 2002). *Calophyllum inophyllum* oil from the fruit has been traditionally used for medicine and cosmetics. For instance in Madagascar it has been used to treat wound, facial neuralgia, skin ailment and hair loss for centuries. Furthermore, it has been used to treat non-chronically skin irritation including burns, rashes, impetigo, insect bites and abrasions (Bhat et al., 2006). It is also applied topically in cases of rheumatism. Besides, the oil is used in varnishes and as lamp oil. In Southern India, the oil obtained from the seeds is utilized to heal skin disease (Satish Lele, 2009). Crude *calophyllum inophyllum* oil generally has high acid value 44 mg KOH/gm (22% FFAs) resulting in a need for a dependable technique to convert this oil to biodiesel. The fatty acid methyl ester of *calophyllum inophyllum* seed oil meets all of the major biodiesel requirements in the United States standard (ASTM D 6751-06) and European Union standard (EN 14214) (Azam et al., 2005). According to Sahoo et al. (Sahoo et al., 2009), the chemical characteristics of the *calophyllum inophyllum* oil biodiesel were found to meet the requirements for diesel engines.

Forest Research Institute Malaysia (FRIM) and Forestry Research and Development Agency, Indonesia (FORDA) joint in forestry research and development especially in biofuel area from year 2007 to 2010 for 5 years (Forest Research Institute Malaysia, 2007). In 2009, a group of researchers from FRIM had joined training on *calophyllum inophyllum* as biofuel to research and exchange information about *calophyllum inophyllum* biodiesel fuel conducted by FORDA in Indonesia (Forestry Research and Development Agency, 2009). This was the very first step of Malaysia involving in *calophyllum inophyllum* research as a biodiesel fuel.

The cultivation of *calophyllum inophyllum* oil can be considered as a potential alternative for renewable energy sources and the oil could be transesterified. However, very limited information is available about the research and biodiesel production from *calophyllum inophyllum* oil. Therefore, further study and research of *calophyllum inophyllum* fuel properties, long-term wear and tribological analysis of biodiesel in diesel engine as well as techno-economic studies need to be carried out before it can be utilized as alternative fuel in near future.

2.5 Production of biodiesel

Researchers have developed various means of biodiesel production from different feedstock. The production of fatty acid methyl ester (FAME) from palm fatty acid distillate (PFAD) having high free fatty acids (FFA) was presented by Chongkhong et al. (2007). During the continuous esterification process, molar ratio of methanol to PFAD at 8:1 with 1.834wt% of H_2SO_4 at 70^oC is considered as optimum condition. After the process, the FFA content decrease from 93wt% to below 2wt%. In order to purify the FAME, neutralization in water was done for 3M NaOH at a temperature of 80 °C for a period of 15 min. This was then followed by transesterification process with 0.396M NaOH in methanol at 65 °C for 15 min (Chongkhong et al., 2007). Besides, Crabbe et al. (2001) analyzed biodiesel production from crude palm oil and evaluation of butanol extraction. The optimized variables molar ratio at 40:1 methanol to palm oil with 5% H_2S0_4 (vol/wt) performed reaction at 95 °C and showed a maximum FAME yield of 97%. Apart from that, Gao et al. (2010) concluded that with 5% KF/Ca-Al (80wt% $KF.6H_2O$) catalyst under temperature of 65 °C and methanol to oil molar ratio 12:1 for 5 hours reaction time, the methyl ester yield could reach 97.98%. However, with the mass ratio 100wt% of $KF.6H_2O$ for catalyst under the same reaction condition, only 3 hours is needed to obtain the methyl ester yield of 99.74%.

Another study revealed that biodiesel production can be carried out by employing non-catalytic supercritical methanol technology from palm oil (Tan et al., 2009b). The research was performed in a batch-type tube reactor with heating that exceeded supercritical temperature and pressure of methanol (239^oC and 8.1MPa respectively). The results showed that non-catalytic supercritical methanol technology needed a mere 20 min reaction time to produce 72% yield of FAME with a temperature 360^oC and molar ratio of palm oil to methanol at 1:30 (Tan et al., 2009b). On the other hand, a study of biodiesel production from palm fatty acids via acid catalysed homogeneous esterification reaction was presented by Aranda et al. (2008). The study shows that methanesulfonic and sulphuric acid were the best catalysts for the reaction with methanol to obtain the greater yields. Melero et al. (2010) produced a FAME yield of 95% in 4 hours with a methanol to oil molar ratio of 20:1 at 140^{o}C using sulfonic acid-modified mesostructured catalysts. Hameed et al. (2009) obtained the optimum biodiesel yield 89% using KF/ZnO catalyst with molar ratio of methanol to oil equal to 11.43:1 and a reaction time of 9.72 hours.

The technique of biodiesel production from crude *jatropha curcas* oil with high FFA content (15%FFA) was performed by Berchmans and Hirata (2008). The *jatropha curcas* methyl ester was produced from crude *jatropha curcas* oil with high FFA via two-step production process. The first stage was acid pre-treatment process which is to reduce the FFA value of *jatropha curcas* oil to below 1%. The second stage is alkali base catalyzed transesterification process with final *jatropha curcas* methyl esters yield of 90%. Patil and Deng (2009) also investigated biodiesel from high FFA *jatropha curcas* oil with two transesterification processes. The two transesterification processes are 0.5% H_2SO_4 acid catalysed esterification process at 40^{o}C with 6:1 of methanol to oil molar ratio, followed by 2% KOH alkali catalysed transesterification reaction with 9:1 of methanol to oil molar ratio at 60^{o}C. This two-step biodiesel production process results in 90–95% yield of *jatropha curcas* biodiesel.

Tiwari et al. (2007) analysed that the optimum combination to reduce the FFA level of *jatropha curcas* oil from 14% to below 1% is 1.43% H_2SO_4 acid catalyst, 0.28 v/v methanol to oil ratio at temperature of 60^{o}C for 88 min reaction time. This was followed by alkali catalysed transesterification process with 0.16 v/v of methanol to oil for 24 min reaction time. This process gave an average yield of biodiesel above 99% along with properties satisfying the biodiesel standards. Besides, the *jatropha curcas* biodiesel production study using a two-step ultrasonic transesterification process was carried out by Deng et al. (2010). The two-step processes were acid esterification and continue with base transesterification process. The authors reported that after the first step of H_2SO_4 pre-treatment process for 1 hour, the acid value of *jatropha curcas* oil decreased from 10.45 to 1.2 mg KOH/g. After that, the second-step transesterification used NaOH as base catalysed. The *jatropha curcas* biodiesel with 96.4% yield and acid value of 0.32mg KOH/g was obtained after 30 min reaction (Deng et al., 2010). Therefore, it is shown that ultrasonic radiation can be implemented effectively in the two-step biodiesel production process with the benefit of time saving.

Corro et al. (2010) presented the biodiesel production from crude *jatropha curcas* oil with a two-step catalyzed process using SiO_2.HF solid catalyst for esterification process followed by transesterification process using NaOH catalyst and methanol. The analysis results demonstrated that the process proposed induced a high quality biodiesel that met the biodiesel specification and requirements. Besides, Lu et al. (2009) found that the jatropha biodiesel yield by transesterification was higher than 98% by using 1.3% of KOH catalyst and 6:1 of molar ratio of methanol to oil at 64^{o}C for 20 min reaction time.

Three stage biodiesel production processes from *calophyllum inophyllum* oil via pre-treatment, alkali catalysed transesterification and post treatment was carried out by Venkanna (2009). The acid esterification with 0.5ml H_2SO_4 at 60^{o}C for 120 min at molar ratio methanol to oil 4:1 gave the optimum conversion efficiency of FFA and the acid value was reduced to 1.64mg KOH/g. However, the maximum reaction conditions for base catalysed transesterification of *calophyllum inophyllum* oil was found to be molar ratio of methanol to oil 8:1 with 1.25% of KOH, at 60^{o}C and 120 min reaction time. It was then followed by gentle washing with distilled water (30% v/v) at 60^{o}C. The study revealed that biodiesel yield for the optimised conditions is 89% and the *calophyllum inophyllum* biodiesel produced is suitable to be used in direct injection diesel engines (Venkanna and Reddy, 2009). On the other hand, Sahoo et al. (2007)

produced high viscosity ($72mm^2/s$ at 40^oC) and high acid value (44mg KOH/gm) *calophyllum inophyllum* oil biodiesel via triple stage transesterification processes. The three step biodiesel production processes from *calophyllum inophyllum* oil are an acid (H_2SO_4) pre-treatment process, alkali (KOH) transesterification reaction using methanol as reagent and followed by post treatment process (Sahoo and Das, 2009). The viscosity and acid value of *calophyllum inophyllum* oil reduce substantially after triple stage transesterification processes. All the characterization tests demonstrated that most of the *calophyllum inophyllum* biodiesel properties are in close concordance with diesel fuel (Sahoo et al., 2007).

The literature imply that the most effective way to produce biodiesel from high FFA feedstock such as *jatropha curcas* and *calophyllum inophyllum* oil is the two step production processes. The two step processes are acid catalysed esterification to reduce the FFA, followed by alkali catalysed transesterification to convert triglyceride to fatty acid alkyl ester which is biodiesel.

2.6 Techno-economic of biodiesel production

There have been a number of techno-economic assessments of biodiesel production which include various feedstocks, production methods and other variables. A summary of these studies is given in Table 2.15.

Marchetti *et al.* (2008) reported that biodiesel production costs of \$0.51/litre and \$0.98/litre via homogeneous and supercritical processes respectively are incurred for a 36 ktons biodiesel plant based on waste cooking oil. Supercritical production processes tend to have lower economic viability due to the higher costs associated with their greater process energy inputs.

A study of biodiesel production from soybean oil was carried out by Hass *et al*. (2006) and You *et al*. (2008) using alkali catalyst. Their results revealed that biodiesel production cost of \$0.53/litre and \$0.78/litre are needed for production capacities of 36 ktons and 8 ktons respectively. Another study conducted using rapeseed gave a price of \$1.15/litre without taking into account the glycerine by-product credit (Apostolakou et al., 2009). Moreover, Sotoft *et al*. (2010) reported a production cost of \$2.04/litre for biodiesel produced from rapeseed oil using an enzyme catalyst. Besides, in another study, \$12 million initial investment is required for 36 ktons palm oil plant which yielded a price of \$0.37/litre based on a raw material cost of \$358/ton for biodiesel (Lozada et al., 2010). Alternatively, a study of a 1 kton of palm oil batch production process via a biological catalyst resulted in a production cost of \$2.30/litre (Jegannathan et al., 2011). In general, it can be observed that biodiesel production using enzymes and biological catalysts are more costly and slower than alkali and acid catalysts. The higher production costs are due to the higher cost of the enzyme catalysts.

Table 2.15: Comparison of biodiesel production cost.

Plant capacity ton/yr	Feedstock	Feedstock cost $/ton biodiesel	Glycerine credit $/ton biodiesel	Biodiesel cost $/litre	Location	Remark	Reference
36,036	Waste cooking oil	445	73.8	0.51	Argentina	Homogeneous alkaline catalyst with acid pre-esterification	(Marchetti et al., 2008)
36,036	Waste cooking oil	905	67.5	0.98	Argentina	Supercritical process	(Marchetti and Errazu, 2008)
8,000	Waste cooking oil	525	91.3	0.95	Canada	Alkaline catalyst	(Zhang et al., 2003)
7,260	Waste cooking oil	248	-	0.58	Japan	Batch, KOH Catalyst	(Sakai et al., 2009)
36,000	Soybean oil	486	35.8	0.53	USA	Sodium methoxide catalyst	(Haas et al., 2006)
8,000	Soybean oil	779	380	0.78	USA	Alkali catalyst	(You et al., 2008)
50,000	Rapeseed oil	1,158	-	1.15	Greece	-	(Apostolakou et al., 2009)
8,000	Rapeseed oil	3,042	2,215	2.04	Denmark	Enzyme Catalyst	(Sotoft et al., 2010)
8,650	Castor oil	1,156	44.1	1.56	Brazil	Alkali catalyst	(Santana et al., 2010)
36,000	Palm oil	358	33.5	0.37	Mexico	Alkali catalyst	(Lozada et al., 2010)
1,000	Palm oil	588	200	2.30	India	Batch, Biological catalyst	(Jegannathan et al., 2011)

CHAPTER 3: METHODOLOGY

3.1 Introduction

The research starts with an investigation on extensive literature collection based on existing research on biodiesel technologies for the transportation sector. Those literatures are available in terms of thesis, books, published journal articles, reports and conference proceeding reports. This study focuses on techno-economic analysis of biodiesel as biofuel for road transportation. In the first stage of this study, energy consumption of the road transport is investigated and the relevant emissions are determined. In the next step, biodiesel production from palm oil, *jatropha curcas* and *calophyllum inophyllum* oil is investigated. Moreover, the life cycle cost and payback period analysis for biodiesel production are carried out to evaluate the economic impact. The energy savings, emission reduction and economic impact through substituting biodiesel fuel are also studied in this chapter. The required equations and mathematical model are developed while the collected data during the survey are presented.

3.2 Data prediction

The polynomial curve fitting method is used to estimate and predict long-term time series. With the aid of this method, the relationship between variable *x* as the function of available data and response y can be illustrated. This method seeks to find a smooth curve that best fits the data but does not necessarily pass through all the data points. Mathematically, a polynomial of order *k* in *x* is an expression in the following form:

$$y = c_0 + c_1x + c_2x^2 + \cdots + c_kx^k \quad \text{….. (3.1)}$$

Prediction of energy consumption

The energy consumption trends in the future are predicted with various methodologies in which the gross domestic product (GDP), population, energy price, past energy consumption and etc. are known as the effective parameters (Kavaklioglu, 2011). In this study, the future energy consumption is considered similar to the trend of previous years by using polynomial curve fitting to estimate long term time series for energy consumption trend. Therefore, Eq. 3.1 is applied to calculate and predict future energy consumption trend.

3.3 Road transport emission

Determining the amount of produced emissions in road transport is the first step to develop effective policies in this field. The COPERT model is one of the most extensive road transport emission modelling methods which is utilized within the European context (Ntziachristos and Samaras, 2000). The mathematical model of COPERT is developed based on a large database that contain information on the national automotive fleet, speed dependent emission functions, fuel consumption, average speed and mileage for the vehicle. Besides the basic emission factors, corrections are also provided for cold starts emission. The amount of greenhouse gas emissions (CO_2, N_2O and CH_4)

produced by different vehicle categories can be computed by COPERT. Besides, it also helps to calculate other major air pollutant emissions like CO, NO_x, NMVOC and PM. Considering the appropriate emission factors, the total emissions can be estimated by combining activity data of each vehicle category. The climate condition and driving situations are the main effective parameters on the emission factors.

3.3.1 Total emissions

Principally, the total emissions can be calculated by summing of the hot emission and cold emission. Hot emission is produced during thermally stabilized engine operation while the cold start emission is produced during engine start from ambient temperature and warming-up effects. Therefore, total emissions can be formulated by the following equation (Ntziachristos and Samaras, 2000):

$$\mathrm{E_{total} = E_{hot} + E_{cold}} \quad \text{….. (3.2)}$$

3.3.2 Hot emissions

Hot emission is the emission that occurs under thermally stabilised engine and exhaust after treatment conditions. Hot emissions are effected by the vehicles travelling distance, the vehicle speed and the engine volume. Besides, different emission factors and mileage per vehicle need to be introduced for each vehicle category. It is assumed that hot emission factors are dependent only on the average speed. Therefore, hot emissions for the pollutants can be calculated by applying equation as below (Ntziachristos and Samaras, 2000):

$$\mathrm{E_{hot;p,j,k} = N_j \times M_{j,k} \times e_{hot;p,j,k}} \quad \text{….. (3.3)}$$

3.3.3 Cold start emissions

Although cold start emission takes place under all three driving modes of urban, rural and highway, it seems to be most likely for urban driving. Principally, the cold start emission occurs for all vehicle categories. Also, the emission factors are only available or can be reasonably estimated for petrol and diesel passenger cars. Therefore, assuming the same behaviour for other vehicles like passenger car, this makes the methodology applicable for all categories of driving modes. Moreover, it is considered that the cold start emission is not a function of vehicle age. These emissions are calculated as an extra emission over the emissions that would be expected if all vehicles were only operated with hot engines and warmed-up catalysts. A relevant factor corresponding to the ratio of cold over hot emissions is applied to the fraction of mileages driven with cold engines. The cold emissions are computed by using the following equation (Ntziachristos and Samaras, 2000):

$$\mathrm{E}_{\mathrm{cold;p,j}} = \beta_{\mathrm{p,j}} \times \mathrm{N}_{\mathrm{j}} \times \mathrm{M}_{\mathrm{j}} \times \mathrm{e}_{\mathrm{hot;p,j}} \times \left({}^{\mathrm{e}_{\mathrm{cold}}}\!/\!{}_{\mathrm{e}_{\mathrm{hot;p,j}}} - 1 \right) \qquad \text{….. (3.4)}$$

The β parameter depends on ambient temperature and the pattern of vehicle used in particular the average trip length (l_{trip}). Due to lack of information on average trip length for all vehicle classes, simplifications have been assumed for some vehicle categories. Kelly et al. (2009) established a value of 12.4 km for the average trip length value based on the available statistical data. Moreover, the mean trip length for total vehicle population can be considered as 17.2 km (Public works department, 2009).

A summary of the required variables and the calculated intermediate values is shown in the flow chart of Figure 3.1. There are four main input categories which are fuel variables, activity data of vehicle, driving condition and other variables like climatic conditions and mean trip distance for COPERT model. The driving condition and other variables are needed to calculate the emission factor of vehicles and compare the fuel balance between statistical and calculation results. The fuel balance are used to make sure and compare the fuel consumption from COPERT calculation results are tally with statistical results obtained from Malaysian Energy Centre (2011). With all input variable the total emissions produced from road transport can be calculated by summation of hot and cold emissions.

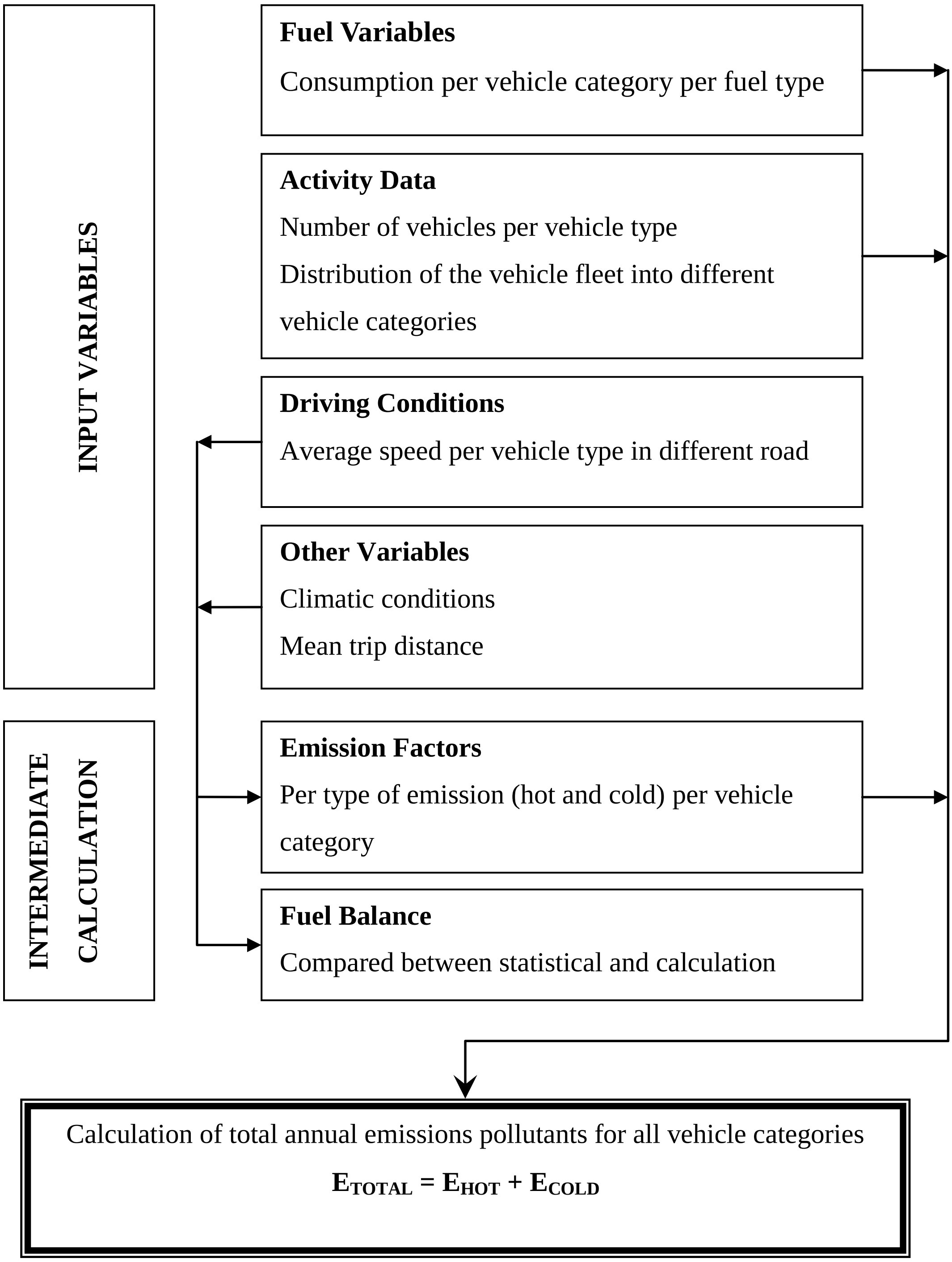

Figure 3.1: Flow chart for COPERT methodology (Ntziachristos and Samaras, 2000).

3.4 Laboratory experiment of biodiesel production

Currently, a large numbers of methods are available and developed for conversion of vegetable oil such as palm oil, *jatropha curcas*, *karanja*, castor and etc. into biodiesel fuel. The micro emulsion, thermal cracking and transesterification process are the three main approaches to produce biodiesel. Biodiesel obtained from thermal cracking and micro emulsion usually have low cetane number and energy content that will lead to incomplete combustion (Leung et al., 2010; Juan et al., 2011). Therefore, transesterification process is used in this study due to its renewability which will result in higher cetane number and lower emission production. Besides, transesterification is most cost efficient method compared with the other processes.

3.4.1 Materials and experiment apparatus

The crude palm oil used in the present research which was obtained from Malacca, Malaysia. However, crude *jatropha curcas* and *calophyllum inophyllum* oil were obtained from West Java, Indonesia which is shown in Figure 3.2.

The crude palm oil, *jatropha curcas* oil and *calophyllum inophyllum* oil were analyzed based on their density at 15^oC, viscosity at 40^oC, flash point, acid value, free fatty acid and fatty acid composition. All the chemicals used in this study such as methanol, potassium hydroxide (KOH), sodium hydroxide (NaOH), hydrochloric acid (HCl), sulphuric acid (H_2SO_4) and etc. were obtained locally. The Schematic diagram of experimental setup and apparatus for esterification and transesterification process are shown in Figure 3.3. The experiments conducted consist of 2 liter double jacketed reactor with tight stopper caps and condenser connected to refrigerator cooling bath. Besides, the condenser is used to retain the vaporization of methanol during the reaction. A water heating bath (Model: Wise Circu Model: WCR-P8) was used to control the reaction temperature and digital stirrer (Model: IKA Eurostar) was used to stir the mixture during the process.

Figure 3.2: Photo of crude palm oil (left), crude *jatropha curcas* oil (center) and crude *calophyllum inophyllum* oil (right).

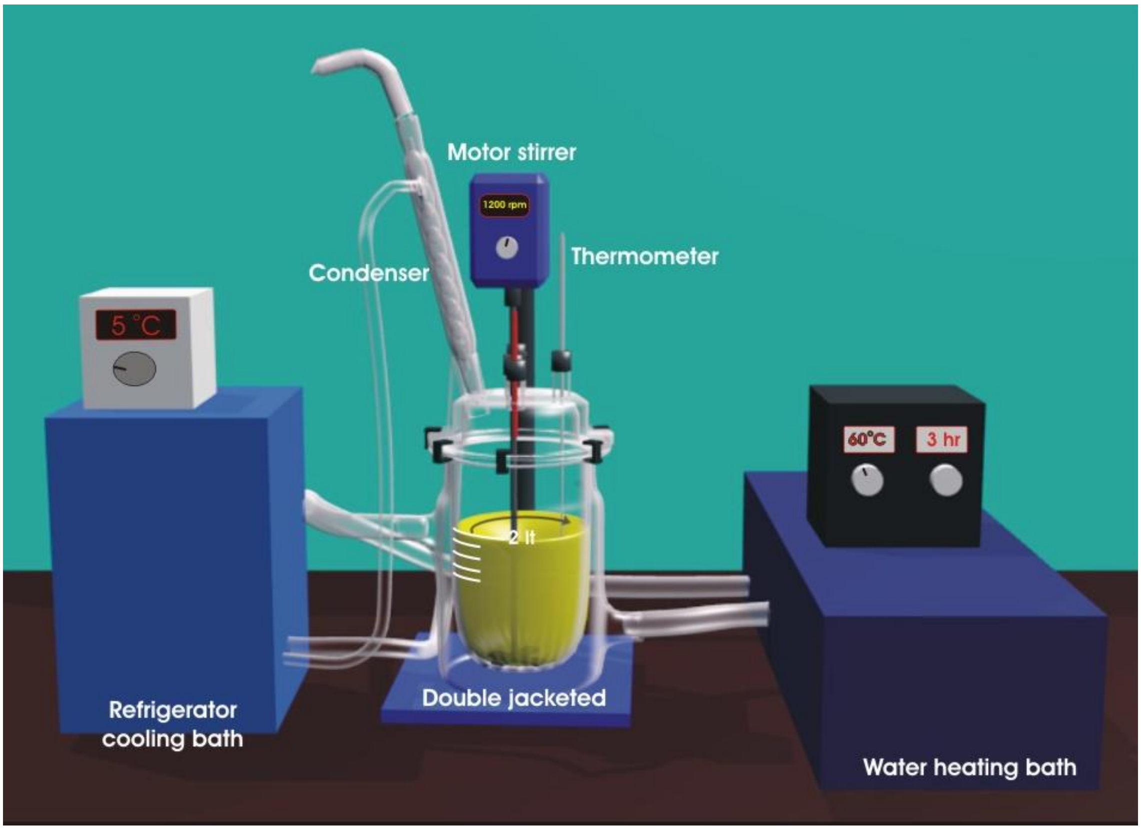

Figure 3.3: Schematic diagram of experimental setup and apparatus for esterification and transesterification process

3.4.2 FFA percentage

Alkaline base titration technique is used to determine the free fatty acid (FFA) of crude vegetable oil and biodiesel. FFA percentage represents the ratio of weight for free fatty acid to weight of oil sample. There is a wide range of different fatty acids and it is not practical to determine the proportions of each in a particular oil sample. Therefore, FFA percentage is expressed as equivalent to oleic acid (OA) which is an average free fatty acid for vegetable oil. In this titration, propanol-2 (isopropyl alcohol) is used as solvent to dissolve the oil sample. A few drops of phenolphthalein solution (phph) were used to indicate the pH of the mixture by observing the colour changes. The mixture was heated around 50^{o}C to make sure the mixture is well mixing. The amount of sodium hydroxide (NaOH) solution that is required to neutralize the dissolved oil is determined to be 0.25M (0.25M NaOH is equivalent to 10g of pure NaOH crystals dissolved in 1L distilled water). While continually stirring this mixture, the NaOH solution was added drop by drop until the colour of mixture turns and remains pink colour. At this point, the number of NaOH solution used was determined and recorded. Thus, the number of moles used for NaOH solution was determined according to the following equation:

$$MO_{NaOH} = C_{NaOH} \times \frac{v_{NaOH}}{1000} \qquad \text{….. (3.5)}$$

Therefore, the equivalent of oleic acid can be determined according to the following equation:

$$m_{OC} = MO_{NaOH} \times M_{OA} \qquad \text{….. (3.6)}$$

Thus, the %FFA can be calculated as shown in following equation:

$$\%FFA = \frac{m_{OC}}{W_{sample}} \times 100 \qquad \text{….. (3.7)}$$

Whereas,

$$C_{NaOH} = \frac{m_{NaOH}/M_{NaOH}}{V_{DW}} \qquad \text{….. (3.8)}$$

3.4.3 Degumming of crude oil

Gum contains phosphate, protein, carbohydrate, water residue and resin. In order to improve the oxidization stability of the final product, the oil is separated from the gums through the degumming process. In this process, the crude oil was heated at a temperature of 60 ℃ and string speed of 1000 rpm. Then, 0.5% (v/v) of phosphoric acid (H_3PO_4, 30% concentration) was added to the preheated crude oil. The process was continued with stirring and the temperature maintained at 60^{o}C for 30 minutes. After that, this mixture was separated by density separation process using a separating funnel for at least 4 hours in which the phosphate compounds resided at the bottom. These gums were separated from the oil and washed several times with distilled water at 40 ℃. After washing, water was evaporated with vacuum pump for 1 hour to avoid the oxidization of oil.

3.4.4 Pre-treatment process (Acid-catalyzed esterification process)

The vegetable oils especially the non-edible oils such as crude *jatropha curcas* and *calophyllum inophyllum* oil have high content of free fatty acid (FFA). High amount of free fatty acid (2% wt of FFA and above) in the crude vegetable oil will react undesirably with the alkali catalyst and cause the formation of soap. This formed soap could prevent separation of the methyl ester layer from the glycerine fraction. The maximum limit of FFA amount is 2% wt and below. Therefore, a pre-treatment process using acid catalyzed esterification is required for the crude oil with high FFA content before the transesterification process. Thus, hydrochloric acid (HCl) is used to convert and reduce the FFA content to below 2% wt in the oil. Therefore, two step processes of acid catalyzed esterification process and base catalyzed transesterification process are used to produce the biodiesel from vegetable oil with high FFA.

On top of that, the crude *jatropha curcas* oil and *calophyllum inophyllum* oil were measured and entered into a jacketed reactor. Then, crude oil was preheated to the temperature of 55-60^{o}C by using a heating circulator. Figure 3.3 shows the utilized experimental set up of the esterification process in this study. The desired amount of methanol and HCl catalyst were measured and mixed together before added into the reactor. The added amounts of methanol vary from 10% to 30% (v/v). However, the added amount of HCl catalyst was in a range of 0.5 to 1.0% (v/v). The mixture was stirred constantly using an overhead stirrer with a constant speed of 1200rpm during the process for 2 hours. Throughout this process, the temperature was kept constant at 55^{o}C. After esterification process the sample oil was removed from the reactor and entered into a separation funnel for 4 hours to remove the water and extra methanol. The upper layer is esterified oil while the water was formed during the reaction process and extra methanol at the lower layer.

3.4.5 Transesterification process of oil

Transesterification methods are used in this study to convert the crude vegetable oil into fatty acid methyl ester (FAME) which is biodiesel. These processes are chemical reaction of a triglyceride molecule or a complex fatty acid with alcohol in the presence of a catalyst to produce fatty acid methyl esters and glycerine as by-products.

The crude oil was measured and placed into a jacketed reactor. Then, crude oil was preheated to the temperature of 55-60^{o}C by using a heating circulator. The exact quantity of alkali catalyst (KOH) and methanol are mixed until all the KOH has been dissolved. After that, the prepared mixtures of methanol and alkali catalyst (KOH) were added into the preheated crude oil. The mixture was stirred constantly at 1200rpm by an overhead stirrer during the transesterification process for 1 to 2 hours. In this process, the temperature was maintained at around 55^{o}C. The experimental setup for transesterification is shown in Figure 3.4.

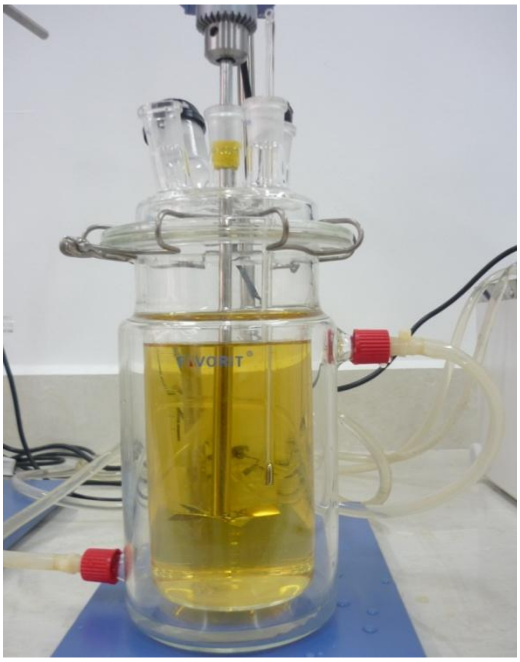

Figure 3.4: Experimental setup of esterification and transesterification process.

The details of the carried out transesterification process in the present study are listed in Table 3.1

Table 3.1: The detail of transesterification process

Crude oil	Alkaline catalyst	Time (min)	Temperature (^{o}C)	Methanol (% v/v)	Catalyst (% w/w)
Palm oil	KOH	60-120	50-60	10-20	0.5-1%
Jatropha curcas	KOH	60-120	50-60	10-20	0.5-1%
Calophyllum inophyllum	KOH	60-120	50-60	10-30	0.5-1%

After completion, the reaction mixture was cooled down to room temperature. Then, the mixture was placed into a separating funnel for 4 hours to ensure that the separation of methyl ester and glycerine phase by gravity occurred completely as shown in Figure 3.5. The upper layer was the biodiesel phase of methyl ester while the lower layer which contained impurities, extra methanol and glycerine were removed.

Figure 3.5: Phase separation process

3.4.6 Post-treatment process

After phase separation of FAME and glycerine, the FAME contains residual catalyst, glycerine, soap, methanol and water. The FAME was purified and washed gently with distilled water at $40^{o}C$ in order to remove impurities. The mixture was allowed to settle under gravity for 3-4 hours in a separating funnel. The settled layer of mixture with impurities was drained out. After the washing process, the final product was evaporated with rotary evaporator at $65^{o}C$ for 30 minutes to remove residual methanol and water.

The flow chart of the applied biodiesel process in this study is shown in Figure 3.6. At the initial stage, degumming process is carried for crude oil to remove the gums containing the oil. The crude vegetable with high free fatty acid (2% wt of FFA and above) will react undesirably with the alkali catalyst and cause the formation of soap. Therefore, acid catalysis pre-treatment process is done to convert the FFA present in the oil before transesterification process. After transesterification process, the produced FAME undergoes the post-treatment process of neutralization and purification to obtain the pure FAME (biodiesel). Finally, the produced biodiesel are tested their properties and compare with ASTM and EN biodiesel standard.

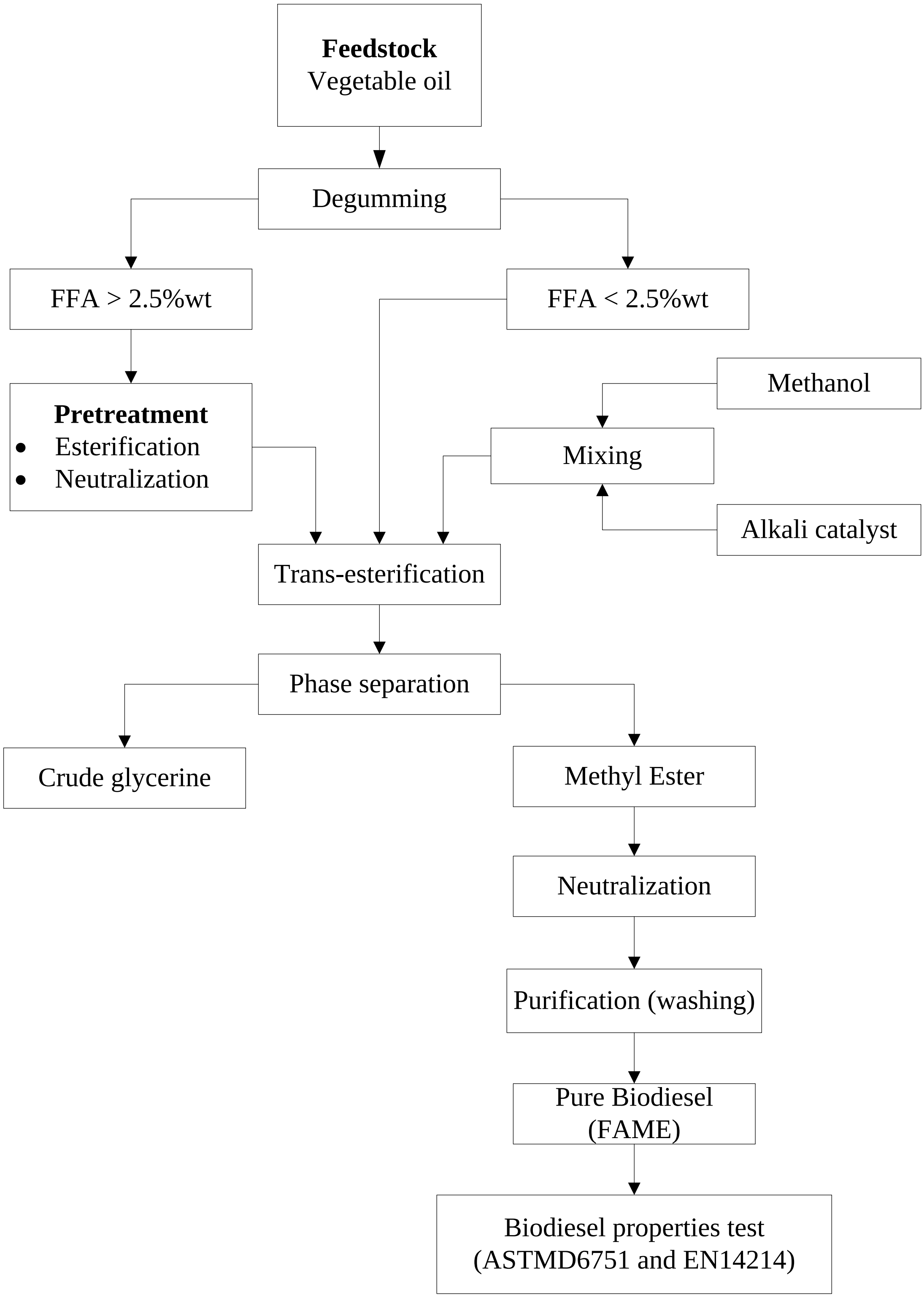

Figure 3.6: Flow chart of biodiesel production process.

3.4.7 Characterization methyl ester (biodiesel)

The physical and chemical properties of the produced palm oil methyl ester (POME), *jatropha curcas* methyl ester (JCME) and *calophyllum inophyllum* methyl ester (CIME) were investigated by applying the ASTM specification: density at 15^{o}C (ASTM D1298) by Anton Paar –DMA 4500 density meter, viscosity at 40^{o}C (ASTM D445) by Anton Paar SVM 3000 viscometer, flash point (ASTM D93) by Petrotest-PM 4 flask point tester, cloud (ASTM D2500) and pour point (ASTM D97) by Normalab-NTE 450 cloud and pour point tester, water content (ASTM D 2709) by Metrohm- Karl Fisher 831 coulometer, acid value (ASTM D663), calorific value by IKA C2000 bomb calorific meter and copper strip corrosion (ASTM D4530) by Stanhope-Seta. All the equipments used for biodiesel characteristics test mentioned above are shown in Appendix C.

3.5 Life cycle cost and payback period

3.5.1 Life cycle cost

Life cycle cost analysis is the total cost of ownership of a plant or system by evaluating the economic benefit of the plant. In this section, life cycle cost model for biodiesel production plant is developed and grouped into six categories as follows (Silalertruksa et al., 2011):

LCC= Capital Cost + Operating Cost + Maintenance Cost + feedstock Cost –Salvage Value – By product credit.

By applying the following approach, the present value calculations are widely used in business and economics to compare cash flows at different times. Writing the life cycle cost in the form of a present value model yields,

$$LCC = CC + \sum_{i=1}^{n} \frac{OC_i + MC_i + FC_i}{(1+r)^i} - \frac{SV}{(1+r)^n} - \sum_{i=1}^{n} \frac{BP_i}{(1+r)^i} \quad \text{….. (3.9)}$$

Present worth factor

Present worth factor (PWF) is the value by which the future cash flow is estimated in order to obtain the current present value of the project. The present worth factor is used to determine the feasibility of biodiesel production plant investment for a given discount rate. The present worth factor in year “i” is defined as (Mahlia et al., 2011),

$$PWF = \frac{1}{(1+r)^i} \quad \text{….. (3.10)}$$

Summing this over a project life of n years yields the compound present worth factor (Mahlia et al., 2011),

$$CPW = \sum_{i=1}^{n} \frac{1}{(1+r)^i} \quad \text{….. (3.11)}$$

$$CPW = \frac{(1+r)^n - 1}{r(1+r)^n} \quad \text{….. (3.12)}$$

Capital cost

The required land area, building construction, equipment and instrumentations for the biodiesel plant are taking into account in capital cost. Capital cost of the initial installation depends mainly on the biodiesel plant capacity. Based on the study by Howell (Howell, 2005) the highest, average and lowest initial capital costs of biodiesel plant based on plant capacity can be expressed in the following equation:

$$CC_{high} = -517.76 \times PC^2 + 252928 \times PC + 3446300 \quad \text{..... (3.13)}$$

$$CC_{avg} = -430.13 \times PC^2 + 205235 \times PC + 2696000 \quad \text{..... (3.14)}$$

$$CC_{low} = -342.49 \times PC^2 + 157542 \times PC + 1945700 \quad \text{..... (3.15)}$$

Operating cost

Operating cost includes the cost of labour, utilities, laboratory services, factory expenses, supervision, administration, transportation cost, all other materials and energy flows except those related to the crude feedstock oil (e.g. CPO, CJO and CBO). Operating costs also include the costs associated with waste water treatment and sludge waste processing to remove residual acids and any other contaminant (e.g. methanol and NaOH). Given their dependence on production capacity, operating costs are calculated by setting a fixed cost per toe of biodiesel produced. Over the life of the plant, total operating costs are,

$$OC = \sum_{i=1}^{n} \frac{OR \times PC}{(1+r)^i} \quad \text{..... (3.16)}$$

Maintenance cost

The annual periodical maintenance and service cost is assumed to be a percentage of maintenance ratio to the initial capital cost. This value is considered to be constant over the entire project lifetime. Maintenance costs are calculated over the life time of the plant as,

$$MC = \sum_{i=1}^{n} \frac{MR \times CC}{(1+r)^i} \qquad \text{….. (3.17)}$$

Feedstock cost

The estimation of feedstock cost is based on the total feedstock consumption for biodiesel production process. Therefore, annual feedstock consumption is determined by adjusting the plant capacity by the feedstock to biodiesel conversion efficiency. The feedstock total consumption can be estimated using the following equation:

$$FU = \frac{PC}{CE} \qquad \text{….. (3.18)}$$

The price of feedstock such as crude palm oil, *jatropha curcas* oil and *calophyllum inophyllum* oil varies over time. In the present study, feedstock prices are estimated considering the historical market price as a reference and an increment with the annual growth rate. Thus, feedstock price is a function of feedstock reference price multiplied by an annual growth rate over the year. This can be represented by the following equation:

$$FP_i^e = RP_i^e \times (1 + s^e)^{i-1} \qquad \text{….. (3.19)}$$

The total feedstock cost is the multiplication of the total annual feedstock consumption and feedstock price on the specific year. Based on this price, total cost of the feedstock over the life of the plant is given by,

$$FC = \sum_{i=1}^{n} \frac{FP_i \times FU}{(1+r)^i} \quad \text{….. (3.20)}$$

Salvage value

The salvage value is the remaining value of the components and assets of biodiesel production plant at the end of the project lifetime. In this study, it has been assumed that a depreciation rate occurs annually. The salvage value model is based on the replacement cost rather than the initial capital cost. The salvage value can be expressed by the following equation:

$$SV = RC \times (1-d)^{n-1} \quad \text{….. (3.21)}$$

Thus, the present value of salvage cost can be calculated as:

$$SV_{PV} = \frac{RC \times (1-d)^{n-1}}{(1+r)^n} \quad \text{….. (3.22)}$$

By product credit

Glycerine is the by-product generated during biodiesel production process. It can be sold as a useful by-product. Calculation is based on the price of glycerine and its production volume which is determined by a plant capacity with glycerine conversion factor. Thus, the by-product credit is the multiplication of glycerine price with the glycerine produced. And, the by-product credit value over the life of the plant is given by,

$$BP = \sum_{i=1}^{n} \frac{GP \times GCF \times FU}{(1+r)^i} \quad \text{….. (3.23)}$$

3.5.2 Payback period

Payback period is the time taken to gain a financial return equal to the original investment cost, with the aid of which the viability and feasibility of the investment can be evaluated. The payback method uses the ratio of capital cost over annual earning as an approach to monitor the project. Taxes are included as a percentage of total biodiesel sales. The payback period is calculated by the following equations (Mahlia et al., 2011):

$$PP = \frac{CC}{TBS - TPC - TAX} \qquad \text{….. (3.24)}$$

Whereby,

$$TBS = \frac{BFP \times PC}{\rho^{e}} \qquad \text{….. (3.25)}$$

$$TPC = 1.1 \times \frac{LCC}{n} \qquad \text{….. (3.26)}$$

$$TAX = (TBS - TPC) \times TR \qquad \text{….. (3.27)}$$

Total biodiesel cost

Final biodiesel costs include the total life cycle cost, distribution cost and profit margin. The total distribution cost and profit margin are 10% of biodiesel production cost. The total biodiesel cost can be estimated using the equation below:

$$TPC = 1.1 \times \frac{LCC}{n} \qquad \text{….. (3.28)}$$

Final biodiesel unit cost

Final biodiesel unit cost is the total biodiesel cost converted into $ per litre of biodiesel fuel. The conversion unit is a function of total biodiesel cost and density of biodiesel divided by annual production capacity. The final biodiesel unit cost can be expressed by the following equation:

$$FBC = \frac{TPC \times \rho}{PC} \qquad \text{….. (3.29)}$$

Fossil diesel cost

The production cost of fossil diesel fuel is estimated based on crude oil price and refining margin of crude oil to diesel. Due to the absence of ex-refinery price for diesel because of the commercially confidential nature of the information, the production cost is estimated by applying US refining margin to Malaysia. The average margin for refining crude oil to diesel fuel is estimated to be 18% (Energy Information Administration, 2011). Thus, fossil diesel cost can be summarized and calculated by following equation:

$$FDC = 1.18 \times \frac{COP}{BL} \quad \text{….. (3.30)}$$

3.5.3 Sensitivity analysis

Sensitivity analysis is applied to predict the outcome of a decision if the situation turns out to be different compared to the key prediction. Sensitivity analysis is an investigation to reveal the variation of the projected performance with change in key assumptions on which the projections are based. It also enables examination of how uncertainty, for example in international prices, can alter project outcomes. Important variables are crude feedstock oil price, discount rate, initial capital cost, oil conversion yield and operating cost. Feedstock's price such as crude palm oil, *jatropha curcas* oil and *calophyllum inophyllum* oil are perhaps the most important. It follows the market value and can be expected to be sensitive to global biodiesel production if growth in this sector occurs. Crude oil supply and demand side factors can also feed into the biodiesel production cost. Moreover, biodiesel production process and oil yield play crucial roles in determining the biodiesel production cost.

3.6 Potential fuel saving and environmental impact

3.6.1 Potential fuel saving

Biodiesel and diesel fuels have different heating value or energy content. Thus, the substitution ratio of biodiesel to diesel fuel is presented by applying the following equation:

$$SR_w = \frac{HVD}{HVB} \qquad \text{….. (3.31)}$$

As the heating value for calculation in Eq. 3.31 is given in MJ/kg, in which the biodiesel substitution ratio is based on a weight basis. However, for the biodiesel fuel substitution based on a volumetric basis should take into account the density of diesel and biodiesel. Therefore, the biodiesel to diesel fuel substitution ratio by volume is calculated by the following equation:

$$SR_{vol} = \frac{HVD}{HVB} \times \frac{\rho_n}{\rho_d} \qquad \text{….. (3.32)}$$

The diesel fuel replacement amount is the total diesel fuel consumption by substituting biodiesel fuel with a propose replacement ratio. It is a function of annual diesel fuel consumption with a replacement ratio which is shown in equation below:

$$DR_i = \eta \times DC_i \qquad \text{….. (3.33)}$$

However, the total biodiesel needs for substituting the diesel fuel is calculated by diesel fuel replacement multiply with biodiesel to diesel fuel substitution ratio as shown below:

$$BC_i = DR_i \times SR_w \qquad \text{….. (3.34)}$$

Finally, the total diesel energy saving is the diesel fuel savings multiplied by the energy content of diesel fuel. The diesel energy savings can be defined as the following equation:

$$TDS = \sum_{i}^{n} DR_i \times EC \qquad \text{….. (3.35)}$$

3.6.2 Potential environmental impact

The environmental impacts such as potential emission reductions, crop land use for biodiesel plant and ecosystem carbon payback period are discussed in this section.

Total carbon saving

Biodiesel is known as a cleaner fuel than diesel which emits less emission and pollutant into the environment. Thus, the potential carbon emission reduction is the difference between the total carbon emitted by biodiesel and the produced carbon emission by diesel. Consequently, the total potential carbon saving is shown by the following equation:

$$TCS_i = TCD_i - TCB_i \qquad \text{….. (3.36)}$$

Whereby, the terms of equation can be calculated by the following equations:

$$TCD_i = DR_i \times EFD \times HVD \qquad \text{….. (3.37)}$$

$$TCB_i = BC_i \times EFB \times HVB \qquad \text{….. (3.38)}$$

Cropland needed

The required cropland for the biodiesel plant is the total feedstock needs to produce the biodiesel fuel. The needed cropland is a function of required feedstock divided by the vegetable or feedstock oil yield which is shown in following equation.

$$CLR = \frac{BC \times 1000}{CE \times OY} \qquad \text{….. (3.39)}$$

Ecosystem carbon payback period

Carbon payback period is used to compare the overall carbon balance from biofuel to compensate for losses in ecosystem carbon stock during land conversion to biofuel cropland. Ecosystem carbon payback period is calculated by the difference between the carbons stock from converting the natural land into biodiesel feedstock cropland divided by the annual carbon savings by using biodiesel fuel. The ecosystem carbon payback period is shown by the equation below:

$$CPP = \frac{LSC - BCC}{TCS/_{CLR}} \quad \text{….. (3.40)}$$

The change of ecosystem carbon stock is caused by the change of land use due to the natural forest replacement with biodiesel feedstock production such as oil palm, *jatropha curcas* and *calophyllum inophyllum*. As a result, the change of ecosystem carbon stock between natural forest and biodiesel feedstock's cropland are considered. In the present study, the estimation of carbon stock is taken from the results carried out by the intergovernmental panel on climate change (IPCC) guidance methodology reports prepared by Gibbs et al. (2008) as shown in Appendix D. From Table A.1, it shows that the carbon stock for tropical forest in Southeast Asia is 229 tC/ha.

3.7 Data collection and assessment

The required survey data of the road transportation and fuel consumption were collected from the Department of Road Transport (2011), Malaysian Energy Centre (2008) and the Department of statistics (2011). All other essential input data are summarized and discussed in this section.

3.7.1 Data input for COPERT model

The input data were collected from various technical sources such as researchers and experienced practitioners in this field, technical note, research papers and survey data from government agencies as well as following the latest market trend.

The ambient temperature and road transport speed limit were collected from the Department of statistics (2011) and Department of Road Transport (2011) respectively. The minimum and maximum ambient temperatures are needed to calculate the cold start emission. The collected temperatures are shown in Table 3.2 based on the monthly basis.

Table 3.2: Average ambient temperature in Malaysia.

Month	Minimum Temperature (^oC)	Maximum Temperature (^oC)
January	22	32
February	22	33
March	22	33
April	23	33
May	23	33
June	23	33
July	23	33
August	23	32
September	22	32
October	23	32
November	23	32
December	22	32

The European Union (EU) fuel regulation and emission standard "EURO I" were officially implemented in Malaysia from 1997 until 2000 for passenger cars, light duty vehicles and heavy-duty vehicles. Malaysia homologated EURO II regulation standard for passenger cars and light duty vehicles since 2000. However, EURO II regulation standard was not implemented for heavy-duty vehicles. Therefore, the EURO I regulations is still applied to the heavy-duty vehicles. Similarly, Malaysian government also adopted the emission European Union (EU) fuel regulation and emission standard. As a result, the COPRET model can be calculated for the road transport emission produced.

The driving mode activity data and conditions affect the quantity of the exhaust emission. The average speeds and average fleet mileage are used as the tuning parameters. The speed limit for road motor vehicles was collected from the department of road transport as shown in Table 3.3. However, similar to the other developing countries, it is difficult to obtain complete statistical and technical data. Estimates of the annual mileage of road vehicles are reported 20,000 km (Aizura et al., 2010).

Table 3.3: Road transport speed limit for various roads.

	Default	Heavy Duty Vehicle	Urban and town area
Highways	110 km/h	80-90 km/h	80-90 km/h
Federal roads	90 km/h	70-80 km/h	60 km/h
State roads	90 km/h	70-80 km/h	60 km/h

3.7.2 Economic indicator for life cycle model

The lifetime of the project has been set to be 20 years by considering one year of construction and start up of the plant. The plant was assumed to operate in 100% capacity during the entire project's lifetime. The initial capital is considered to be paid by private investment and no loans have been taken into account. It is assumed that the selling price of the produced biodiesel and glycerine does not vary over time. Table 3.4 shows the summary of economic data and indicators.

Table 3.4: Summary of economic data and indicators.

Item	Data
Project lifetime	20 years
Plant capacity	50 ktoe
Depreciation model	10% annually
Operating rate:	
Palm biodiesel	$250/toe of FAME
Jatropha curcas biodiesel	$300/toe of FAME
Calophyllum inophyllum biodiesel	$300/toe of FAME
Maintenance cost	2% of capital cost annually
Replacement cost	$10 Million
Tax ratio	15% of biodiesel profit
Glycerine price	$ 0.25/kg
Discount rate	8%

Diesel and biodiesel fuel's properties such as calorific value, density, LCA carbon factor and related conversion yield are shown in this section. The life cycle assessment of carbon emission of biodiesel fuel includes the production of the feedstock, transesterification process as well as the combustion phase of biodiesel fuel. All the input data for this study are summarized in Table 3.5.

Table 3.5: Summary of diesel and biodiesel fuel properties (Sahoo and Das, 2009).

Property	Diesel	Palm Biodiesel	*Jatropha curcas* bioidesel	*Calophyllum Inophyllum* biodiesel
Nett calorific value (MJ/kg)	43.4	35.0	38.5	39.3
Density (kg/m^3)	837	879	862	869
LCA carbon emission factor (kg/GJ)	88.0	61.8	42.2	64.4
Yield of FAME (biodiesel) conversion	-	90	87	85
Yield of glycerine produce	-	9%	10%	5%
Vegetable oil yield (kg/ha)		3740	1590	4680

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter contains the results and discussion for biodiesel production and techno-economic analysis of oil palm, *jatropha curcas* and *calophyllum inophyllum* oil as biofuel. Firstly, the trend of energy and emission pattern for the transportation sector in Malaysia is analyzed. In addition, the results of the laboratory experiments of biodiesel production from oil palm, *jatropha curcas* and *calophyllum inophyllum* oil are explained. Then, techno-economic and life cycle cost of biodiesel production plant are discussed. Potential energy saving and emission reduction in road transport for selected biodiesel are calculated as well. After that, the impact of implementation of biodiesel in transportation sector on energy, economic and environmental are discussed. Finally, the saving and subsidy costs of replacing diesel by biodiesel are presented and analyzed.

4.2 Prediction of diesel fuel consumption

The future diesel fuel consumption of the transportation sector is predicted by applying the polynomial curve fitting method as shown in Eq. 3.1 with assessment of the existing historical data from 1980 to 2010. Based on the listed historical data in Figure 2.8, the diesel fuel consumption is projected by the following polynomial equation and the graph is illustrated in Appendix E, Figure A.1.

$$y = 3.8076x^2 + 74.889x + 645.12, \quad R^2 = 0.8957 \qquad \ldots\ldots (4.1)$$

The quadratic equation as shown in eq. 4.1 is the best curve fitting to connect all the historical data with $R^2 = 0.8957$. Thus, the future diesel fuel consumption for motor vehicles from year 2012 to 2031 in Malaysia is predicted using eq. 4.1 and the results are shown in Table 4.4. Based on the projection results, the total diesel consumption will increase to 14,368 ktoe or 16,972 million litres in 2031.

Table 4.1: Diesel fuel consumption projection for transportation sector from 2012 to 2031.

Year	Diesel fuel consumption (ktoe)	Diesel fuel consumption (million litres)
2012	6,941	8,056
2013	7,263	8,429
2014	7,593	8,812
2015	7,931	9,205
2016	8,276	9,605
2017	8,629	10,015
2018	8,989	10,433
2019	9,357	10,860
2020	9,733	11,296
2021	10,116	11,741
2022	10,507	12,194
2023	10,906	12,657
2024	11,312	13,129
2025	11,726	13,609
2026	12,147	14,098
2027	12,576	14,596
2028	13,013	15,103
2029	13,457	15,618
2030	13,909	16,143
2031	14,368	16,675

4.3 Road transport emissions

The estimated results of road transport emissions by COPERT 4 for the year 2010 are shown in Table 4.2. The results of the pollutant emissions were indicated based on the vehicle type. The first three rows of the table show the amount of direct greenhouse gases (GHG) included CO_2, CH_4 and N_2O which are 48,361 million kg, 17.15 million kg and 1.86 million kg respectively. The results obtained are inline and close with the estimation by (International Energy Agency, 2010) which the total CO_2 emissions produced from road transports are around 42.2 billion kg in 2008. On the other hand, (Safaai et al., 2010) predicted the total CO_2 emissions are around 70 billion kg for transportation section in 2010. Besides, the passenger cars are the main source of producing direct GHG pollutants which is around 60%, 42% and 78% of the total CO_2, CH_4 and N_2O emissions respectively. Motorcycles are the major contribution in producing CH_4 emission that is 8.6 million kg and 50% of the total CH_4 emission. The other rows in Table 4.2 reveal that the other pollutant emissions which are CO, NO_x, NMVOC and exhaust particulate matters (PM). Passenger cars and motorcycles can be considered as the main source of CO and NMVOC emissions. Besides, passenger cars also produced 178 million kg of NO_x and 2 million kg of particulate matters. Light duty vehicles and heavy duty vehicles with diesel engine are the major contributors of PM exhaust emissions with share of 61% of total particulate matters exhaust.

The other pollutant gases like CO, NO_x and NMVOC do not contribute to radioactive forces but their presence affects the concentration of important components such as ozone. Therefore, those gases are called indirect greenhouse gases. Table 4.3 displays the CO_2 equivalents of the gaseous emissions for the direct and indirect greenhouse gases with the global warming potentials (GWP). The CO_2 equivalents for the gas were calculated by multiplying the quantities of the gas with their GWP value. Table 4.3 shows that the total CO_2 equivalent emission for road transports in Malaysia is 67,471 million kg. The CO_2 emission is the largest emitter of GHG which occupied 71.7% of the total CO_2 equivalents followed by NO_x which accounts for 19.8%.

Table 4.2: Road transport emission for year 2010 in Malaysia (million kg).

Emissions	Passenger cars	LDV	HDV	Buses	Motorcycles	Total
CO_2	29,326.15	4,532.38	7,701.07	1,402.12	5,399.87	48,361.60
CH_4	7.22	0.23	0.92	0.17	8.60	17.15
N_2O	1.47	0.04	0.21	0.03	0.13	1.86
CO	953.92	15.48	19.20	4.56	934.37	1,927.53
NO_x	178.16	25.32	96.56	17.92	15.41	333.37
NMVOC	100.68	1.81	5.46	1.79	116.03	225.77
PM	2.03	3.72	3.84	0.77	2.02	12.39

Table 4.3: CO_2 equivalent emissions (million kg)

GHG	Emissions	GWP	CO_2 equivalent	%
CO_2	48,361.60	1	48,361.60	71.7
CH_4	333.37	40	13,334.67	19.8
N_2O	1,927.53	2	3,855.05	5.7
CO	225.77	4	903.08	1.3
NO_x	1.86	320	596.49	0.9
NMVOC	17.15	24.5	420.18	0.6
Total			67,471.06	100.0

4.4 Biodiesel production

4.4.1 Properties of crude vegetable oil

The crude vegetable oils used in this study were palm, *jatropha curcas* and *calophyllum inophyllum* oil as shown in Figure 3.2. The characteristics and the physicochemical properties of these three crude oils such as density, flash point, viscosity, acid value and free fatty acid composition were determined and shown in Table 4.4. These three crude vegetable oils have high viscosity which is recorded to be 41.63, 28.35 and 53.17 cSt respectively. Besides, the acid value of *jatropha curcas* and *calophyllum inophyllum* oil was above 4 mg KOH/g, measuring at 46.8 and 59.3 mg KOH/g respectively. Thus, a two-step catalyzed process was needed to produce the biodiesel fuel from crude *jatropha curcas* and *calophyllum inophyllum* oil.

Furthermore, it has been found that the crude *jatropha curcas* and *calophyllum inophyllum* oil contain a higher amount of unsaturated fatty acids (oleic and linoleic) than saturated fatty acids (palmitic and stearic). These results are in agreement with the existing results in the literature such as Sharma et al., (2008), Sahoo et al., (2007), Tong et al., (2011), Hathurusingha, (2011) and Kumar & Sharma (2011).

Table 4.4: Physicochemical properties of crude palm, *jatropha curcas* and *calophyllum inophyllum* oil

Parameters	Palm oil	*Jatropha curcas* oil	*Calophyllum inophyllum* oil
Density 15^{o}C (kg/m^3)	0.919 ±0.001	0.915 ±0.001	0.951 ±0.001
Viscosity at 40^{o}C (cSt)	41.63 ±0.01	28.35 ±0.01	53.17 ±0.01
Flash point (^{o}C)	181 ±1	170 ±1	148 ±1
Free fatty acid (%FFA)	0.424 ±0.001	23.382 ±0.001	29.661 ±0.001
Acid Value (mg KOH/g)	0.848 ±0.001	46.764 ±0.001	59.332 ±0.001
Fatty acid composition (FAC)			
Lauric (12:0)	0.2	0.0	0.0
Myristic (14:0)	0.9	0.1	0.0
Palmitic (16:0)	38.6	13.0	14.7
Palmitoleic (16:1)	0.2	0.7	0.3
Stearic (18:0)	4.4	5.8	13.2
Oleic (18:1)	44.6	44.5	46.1
Linoleic (18:2)	10.5	35.4	24.7
Linolenic (18:3)	0.2	0.3	0.2
Arachidic (20:0)	0.4	0.2	0.8
Saturated	44.5	19.1	28.7
Unsaturated	55.5	80.9	71.3
Total	100.0	100.0	100.0

On the other hand, the comparison of fatty acid composition of palm, *jatropha curcas* and *calophyllum inophyllum* oil is shown in Figure 4.1. Palmitic and oleic are the dominant fatty acids in the crude palm oil whilst oleic and linoleic are the dominant fatty acids in crude *jatropha curcas* and *calophyllum inophyllum* oil.

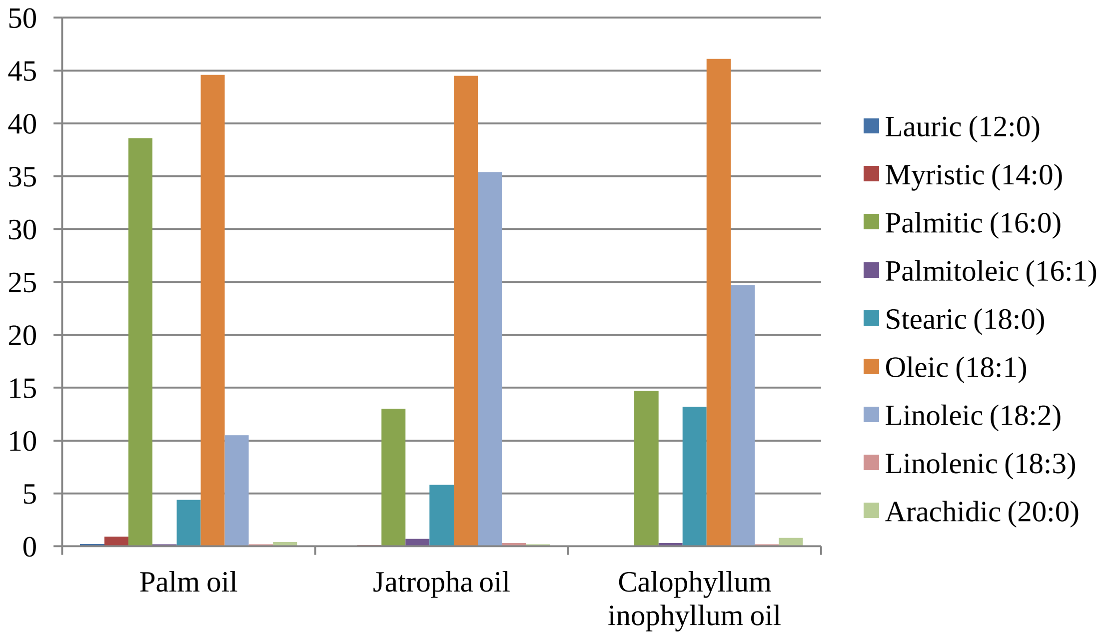

Figure 4.1: Comparison of fatty acid composition of palm, *jatropha curcas* and *calophyllum inophyllum* oil.

4.4.2 Degumming process

Crude *calophyllum inophyllum* oil contains gum such as phosphate, protein, carbohydrate, water residue and resin. Therefore, degumming process is required to separate oil from the gums in order to improve the oxidization stability of the oil. Table 4.5 shows the physicochemical properties of crude and degummed *calophyllum inophyllum* oil. It is shown that density, viscosity, acid value and free fatty acid value decreased after degumming process. Apart from that, transmission has increased and absorbance has decreased attributed to the removal of gum from the oil.

Table 4.5: Physicochemical properties of crude and degummed *calophyllum inophyllum* oil

Property	Before degumming	After degumming
Density at 15 ℃ (g/cm^3)	0.951 ±0.001	0.949 ±0.001
Viscosity at 40 ℃ (cSt)	53.17 ±0.01	43.96 ±0.01
Acid value (mg KOH/g)	59.33 ±0.01	57.92 ±0.01
Free fatty acids (%)	29.66 ±0.01	28.96 ±0.01
Transmission (%)	0 ±0.01	79.6 ±0.1
Absorbance	3.4 ±0.1	0.099 ±0.001
Colour	Dark green	Reddish

4.4.3 Acid catalyzed esterification process

The FFA for crude *jatropha curcas* and *calophyllum inophyllum* oil are 23.38% and 29.66% respectively. Acid catalyzed esterification process is used to reduce the high content of FFA in the crude *jatropha curcas* and *calophyllum inophyllum* oil. In order to avoid soap formation, the FFA content should be reduced to below 2% wt before undergoing the transesterification process.

The crude *jatropha curcas* oil with high FFA content initially undergoes the hydrochloric acid (HCl) catalyzed esterification to reduce the FFA amount to below 2%. The esterification process was done using 1% v/v of HCl and 20% v/v of methanol in oil at 60^{o}C. The process continues string the mixture with a constant speed of 1200rpm and maintains the temperature at 60^{o}C for 2 hours. After the conducted process, the FFA amount is reduced to 1.2%.

Crude *calophyllum inophyllum* oil also have high amount of FFA which is equal to 28.96% after degumming process. Thus, same as crude *jatropha curcas* oil, *calophyllum inophyllum* oil was also initially treated with acid catalyzed esterification using hydrochloric acid (HCl) and methanol to reduce the FFA content. This pre-treatment process was done using 1% v/v of HCl and 25% v/v of methanol in oil at 60^{o}C. Again, the process is continued by stiring the mixture with a constant speed of 1200rpm and maintain at 60^{o}C for 2 hours. The process reduced the FFA content from 28.96% to 2%.

4.4.4 Alkaline catalyzed transesterification process

In the present study, alkaline catalyzed transesterification methods are applied to convert the crude vegetable oil into fatty acid methyl ester (FAME) which is biodiesel. Potassium hydroxide (KOH) is used as alkali catalyzed to produce biodiesel.

The optimum conversion yield of palm oil is 90% by using 20% v/v of methanol and 0.5% w/v of KOH at 55^{o}C for 1 hour. On top of that, the amount of glycerine produced during the transesterification process is around 9%.

However, *jatropha curcas* oil managed to achieve a conversion yield of 87% in the presence of 20% v/v of methanol and 0.5% w/v of KOH at 55^{o}C for 2 hour process. Besides, 10% of glycerine is produced during the transesterification process as by-product.

Lastly, the transesterification reaction for *calophyllum inophyllum* oil was conducted by using 20% v/v of methanol and 0.5% w/v of KOH at 55^{o}C for 2 hours. The final biodiesel obtained from *calophyllum inophyllum* oil is 85% and 5% of glycerine is collected as by-product during the process. The summary of biodiesel esterification and transesterification process are shown in Table 4.6.

Table 4.6: Summary of biodiesel esterification and transesterification process.

Feedstock	Process	Acid/alkaline catalyst	Time[a] (hour)	Temperature[a] (^{o}C)	Methanol[a] (% v/v)	Conversion (%)
Palm oil	1 step	KOH	1	55	20	90
Jatropha curcas	2 steps	HCl/KOH	2/2	60/55	20/20	87
Calophyllum inophyllum	2 steps	HCl/KOH	2/2	60/55	25/20	85

[a]Reaction time, temperature and methanol ratio of acid/alkaline catalyst

4.4.5 Biodiesel properties of palm, *jatropha curcas* and *calophyllum inophyllum*

The obtained biodiesel from the palm, *jatropha curcas* and *calophyllum inophyllum* are shown in Figure 4.2 and Table 4.7 summarized the important physiochemical properties results of biodiesel produced. In this section, the physiochemical properties of produced biodiesel from these three fuels are discussed. Those reported results are compared with ASTM D6571 and EN 14214 biodiesel standards. All specified properties obtained from palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel are in acceptable ranges according to ASTM D 6571 and EN 14214 standards.

Figure 4.2: Palm (left), *jatropha curcas* (centre) and *calophyllum inophyllum* biodiesel (right)

Table 4.7: Physiochemical properties of palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel compare with ASTM & EN standard.

Fuel Properties	Palm biodiesel	*Jatropha curcas* biodiesel	*C. inophyllum* biodiesel	ASTM D6751	EN14214
Density (kg/m^3)	885.4±0.001	868.9±0.001	872.3±0.001	-[a]	860-900
Viscosity at 40^{o}C (cSt)	4.00±0.01	4.66±0.01	2.85±0.01	1.9–6.0	3.5-5.0
Calorific value (MJ/kg)	35.0±0.1	38.5±0.1	39.3±0.1	-[a]	-[a]
Acid (Neutralization) value (mg KOH/g)	0.28±0.01	0.41±0.01	0.33±0.01	Max.0.50	Max 0.50
Flash point (^{o}C)	162.5±0.1	158.3±0.1	141.0±0.1	Min 130	Min 101
Cloud point (^{o}C)	11.7±0.1	9.8±0.1	10.4±0.1	-3-12	-[a]
Pour point (^{o}C)	9.6±0.1	8.7±0.1	6.0±0.1	-15-10	-[a]
Water content (mg/kg)	198±1	161±1	133±1	-[a]	Max 500
Copper strip corrosion (50^{o}C; 3 hrs)	1a	1a	1a	Max No. 3	Class 1

[a] Not specified

Density is one of the important properties of biodiesel that influences the efficiency of the fuel atomization in airless combustion systems. According to ASTM D6751 and EN 14214 standards, the density of biodiesel fuel at 15^{o}C must be between 860-900 kg/m^3. Table 4.14 shows that the density of palm oil, *jatropha curcas* and *calophyllum inophyllum* biodiesel obtained in this study was 885.4kg/m^3, 868.9kg/m^3 and 872.3kg/m^3 respectively. Density of fuel also affects the exhaust emissions in which high density fuel cause an increase in particular matter and NO_x emission (Canakci and Sanli, 2008). Generally, biodiesel has slightly higher density than diesel.

Kinematic viscosity is another important property associated with fuel atomization as well as fuel injection into the combustion chamber. High viscosity may lead to the soot formation and engine deposits due to insufficient fuel atomization. According to ASTM D6751 and EN 14214 standards, viscosity must lay between 1.9-6.0cSt and 3.5-5.0cSt respectively. Table 4.14 shows that the viscosity of the obtained POME, JCME and CIME were 4cSt, 4.33cSt and 2.85cSt respectively. The viscosity of crude vegetable oil was reduced after the transesterification process. It can be concluded that the viscosity of the produced biodiesels are in line within the range specified in biodiesel standards.

Calorific value is not specific either in ASTM D6751 or EN14215 standard. However, calorific value is an important property in the selection of a fuel. Typically, the calorific value of biodiesel is lower than diesel due to their oxygen content. The obtained calorific values for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel were 35.0 MJ/kg, 38.5MJ/kg and 39.3MJ/kg respectively. Those values are lower than diesel fuel which is recorded to be 43.4MJ/kg. It can be seen that the *calophyllum inophyllum* biodiesel has the highest calorific value among these three biodiesel.

Another important criterion for the biodiesel fuel selection is flash point. Flash point is the temperature at which the fuel will ignite when exposed to a flame or spark. Flash point of biodiesel fuel is not related directly to engine performance. However, flash point is measured to meet safety requirements for fuel handling and storage. According to the biodiesel standards, biodiesel fuel must have a flash point higher than 130^{o}C. The observed flash point for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel was 162.5^{o}C, 158.3^{o}C and 141.0^{o}C respectively. Generally, the flash point of biodiesel is higher than the diesel which is safe for transport and storage purpose. The flash point of these three crude oil feedstock are far above in comparison with the diesel fuel that reflects the non-volatile nature of the fuel.

The cold flow properties for biodiesel fuel are cloud and pour points. Cloud point is the temperature at which the biowax in biodiesel form a cloudy appearance when the fuel is cooled. However, pour point is the minimum temperature at which biodiesel fuel becomes semi solid and losses its flow characteristics. Most of the biodiesel fuels have higher cloud and pour point compare with the diesel fuels. These poor cold properties are one of the critical obstacles against the widespread of biodiesel fuel. The cloud point of palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel was measured as 11.7^{o}C, 9.8^{o}C and 10.4^{o}C respectively. On the other hand, the pour point of the palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel were obtained 9.6^{o}C, 8.7^{o}C and 6.0^{o}C respectively. The ASTM standard for cloud and pour point is between -3-12^{o}C and -15-10^{o}C respectively. Among these three biodiesel fuels, *jatropha curcas* and *calophyllum inophyllum* biodiesel have better cold flow properties than palm biodiesel.

Free fatty acid can affect and cause the corrosion of internal combustion engine and some other metal parts. Therefore, ASTM biodiesel standard only approved a maximum acid value of 0.5mg KOH/g. The acid values were 0.28, 0.41 and 0.33 mg KOH/g for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel respectively. The obtained results met the biodiesel standard.

Copper corrosion test is to measure the corrosion tendency of fuel to the internal combustion engine and the copper, brass or bronze parts in the engine. A copper strip is heated to 50^{o}C in a fuel bath for three hours followed by comparison with ASTM standard strips to determine the degree of corrosion. The results show that the copper strip corrosion for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel was 1a which is in agreement with ASTM and EN biodiesel standards.

Water content of biodiesel can reduce the heat of combustion and cause corrosion of vital components of the fuel system. The maximum limit of water content is determined to be 500 mg/kg according to EN 14014 biodiesel standard. The results show that water content for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel is below than 200 mg/kg, which is in agreement with the specified limitation value in EN 14104 standard.

4.5 Life cycle cost

Life cycle cost analysis is used to estimate the biodiesel production cost over a lifetime of 20 years. Life cycle costs can be summarized as an economic model to evaluate a project. The life cycle cost is driven by engineering details for economic calculations and evaluation. Life cycle cost model provides good assessment for long term cost effectiveness of a plant or project to build a sound business case for action. The following section shows the results of life cycle cost assessment for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel production in Malaysia.

Life cycle cost is calculated for a typical 50 ktoe biodiesel plant located in Malaysia using the data of Table 3.4. The life cycle costs of biodiesel production from palm, *jatropha curcas* and *calophyllum inophyllum* oil are calculated based on Eq. 3.9. The results are presented in Figures 4.3 – 4.5.

Life cycle cost of biodiesel production from palm, *jatropha curcas* and *calophyllum inophyllum* are illustrated in Figure 4.3. The life cycle cost is shown in the present value by considering 8% discount rate. The results revealed that palm biodiesel production cost is higher compared to *jatropha curcas* and *calophyllum inophyllum* biodiesel. However, the life cycle cost of *jatropha curcas* and *calophyllum inophyllum* biodiesel production are almost similar.

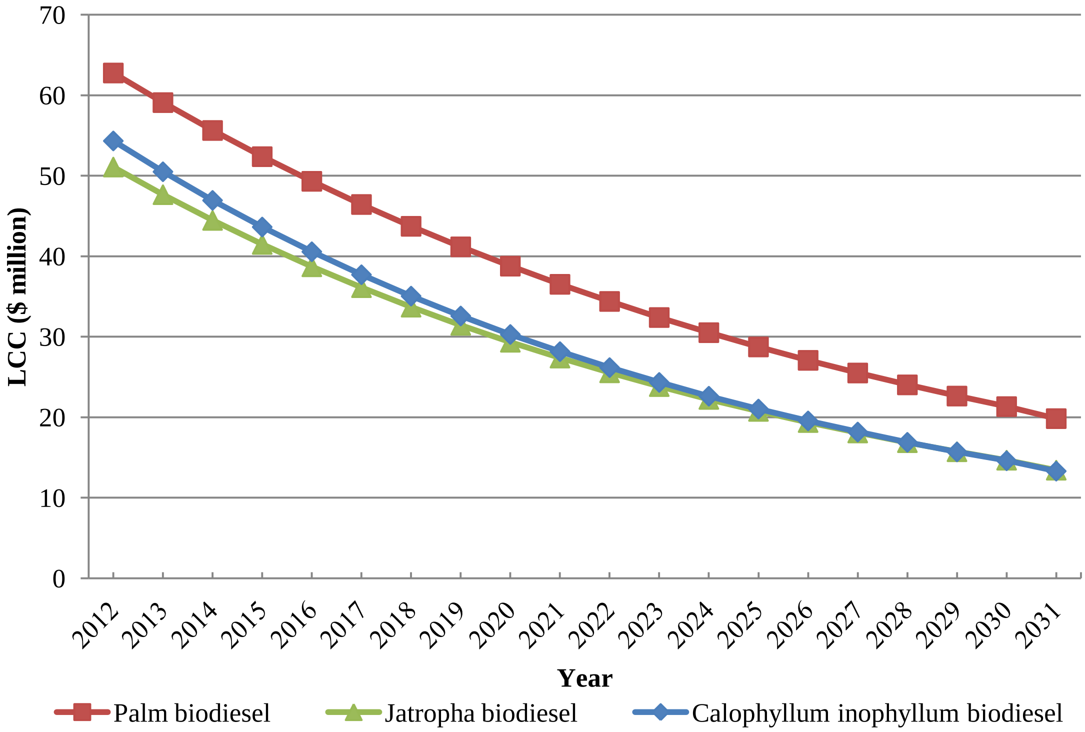

Figure 4.3: Life cycle cost of biodiesel production over 20 years life time.

Figure 4.4 and 4.5 illustrate the comparison of life cycle cost for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel production and the distribution of biodiesel production life cycle cost. The largest share of life cycle cost of biodiesel production belongs to the feedstock price which is $643.3, $438.6 and $470 million for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel respectively, followed by operating, capital and maintenance cost. Besides, the sale of by-products glycerine is a source of income which contributes $16.4, $17.3 and $13.5 million over the life of the project for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel respectively.

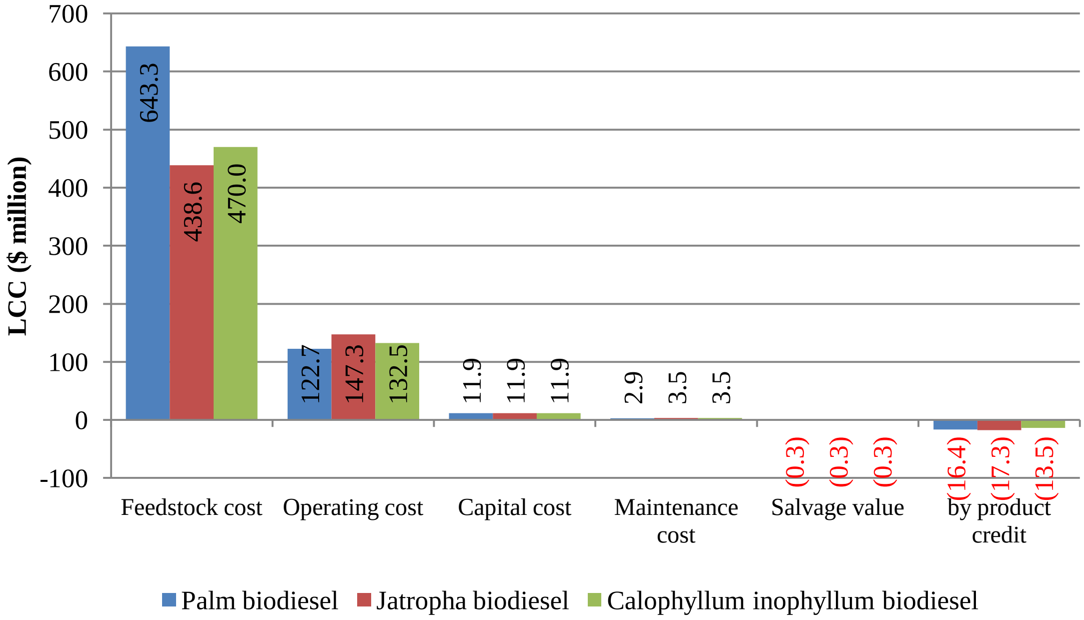

Figure 4.4: Comparison of life cycle cost for palm, *jatropha curcas* and *calophyllum inophyllum* production.

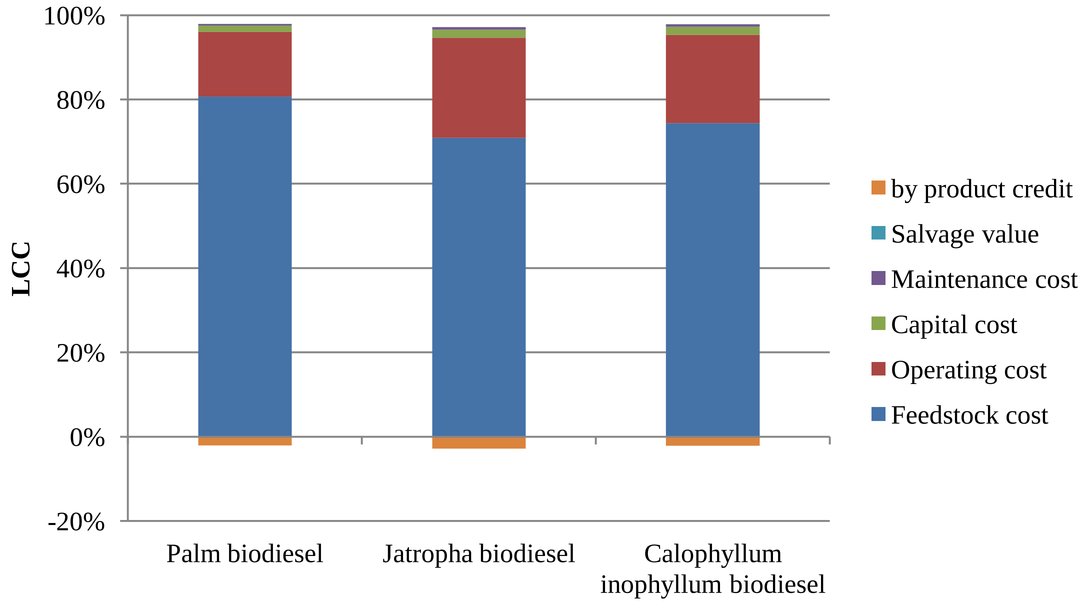

Figure 4.5: Distribution of biodiesel production life cycle cost.

The summary of life cycle cost and payback period for biodiesel production are presented in Table 4.8. It is shown that the total life cycle costs of biodiesel production are $780, $601 and $617 million for palm, *jatropha curcas* and *calophyllum inophyllum* respectively without taking into account the glycerine credit. The largest economic factor for the life cycle cost of biodiesel production is feedstock which is about 82%, 73% and 76% of total life cycle cost for palm, *jatropha curcas* and *calophyllum inophyllum* oil respectively. Palm oil biodiesel accounted the highest percentage of feedstock cost among other biodiesel productions due to the high price of crude palm oil. The high demand of palm oil and the price of crude oil which hit new highest record of US$136/barrel in July 2008 are the main causes of the augmentation of the crude palm oil price in recent years. Moreover, the other important costs are operating costs such as labour cost, utilities, laboratory, administration cost as well as other raw materials and chemical used in the process. The total operating cost is ranged from 16% to 24% of the total life cycle cost.

The sales of by-products are a source of income and it contains around 2% of the biodiesel production cost. On top of that, the total biodiesel production life cycle cost decreased to $764, $583 and $604 million by taking into account the glycerine credit for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel respectively. On the other hand, the unit production cost of palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel are calculated to be $0.672/litre, $0.503/litre and $0.525/litre respectively. The resulted palm biodiesel cost in this study are lower than the $2.30/litre obtained by Jegannathan et al. (Jegannathan et al., 2011) which made use of a batch process via a biological catalyst. However, this cost is higher than the $0.37/litre of Lozada et al. (Lozada et al., 2010) which used a similar production process to that used here, although from a smaller 36 ktoe plant.

Payback period as an effective tool is used to determine the required time to recover the investment. This is very important for financial management to monitor the recovery time of the project. The payback period for 50 ktoe of palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel production plant was found to be 3.52, 1.90 and 1.98 years respectively. Being less than one third of the 20 year project life, this result indicates that the project is economically feasible.

Table 4.8: Summary of life cycle cost and payback period for biodiesel production.

	Palm biodiesel		*Jatropha curcas* biodiesel		*calophyllum inophyllum* biodiesel	
	$	%	$	%	$	%
Capital cost	11,882,425	1.52	11,882,425	1.98	11,882,425	1.92
Operating cost	122,726,843	15.72	147,272,211	24.51	132,544,990	21.46
Maintenance cost	2,916,585	0.37	3,499,902	0.58	3,499,902	0.57
Feedstock cost	643,348,614	82.42	438,583,834	72.98	470,045,283	76.09
Salvage value	260,841	0.03	260,841	0.04	260,841	0.04
by product credit	16,363,579	2.10	17,326,142	2.88	13,542,272	2.19
LCC (w/o by product credit)	780,613,626		600,977,532		617,711,759	
Total life cycle cost	764,250,047		583,651,389		604,169,487	
Production unit cost ($/litre)	0.672		0.503		0.525	
Payback period (year)	3.52		1.90		1.98	

4.6 Sensitivity analysis

Sensitivity analysis is used to predict the outcome of a decision if the parameter value turns out to be different compared to the planned key prediction. Sensitivity analysis investigates the impact of input parameter variation on the model's conclusions. Figure 4.6 shows the results of sensitivity analysis for palm biodiesel production for five input variables. The legends on the left of the figure give the variation in the sensitivity variable from favourable, to planned and to unfavourable. From the obtained results, it is obvious that crude palm oil price, discount rate, oil conversion yield and operating cost affect the biodiesel production cost. As expected, variation in the price of CPO represents the dominant impact on life cycle cost. For instance, CPO price of $700/ton reduces the life cycle cost to $570 million compared to more than $950 million of life cycle cost for CPO price of $1300/ton. The examined CPO price range covers a typical variation of the crude oil price for the last two years. Furthermore, the present value discount rate also causes a huge impact on the life cycle cost of palm biodiesel production. Variation in oil conversion yield and operating costs have the lower impact of the on-going costs, but together can offset significant variation in biodiesel production cost. Continual improvement in the biodiesel conversion processes and greater operating efficiency can lead to a significant reduction in overall biodiesel production costs.

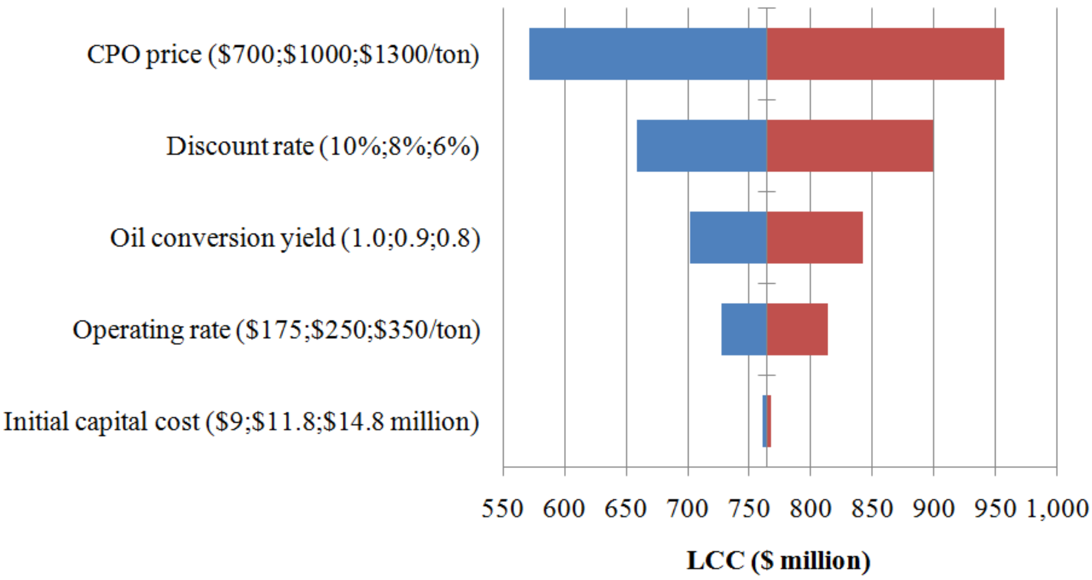

Figure 4.6: Sensitivity analysis of life cycle cost for palm biodiesel production.

Figure 4.7 illustrates the sensitivity analysis results of *jatropha curcas* biodiesel production for five input variable of crude *jatropha curcas* price, discount rate, oil conversion yield, operating cost and capital cost. The legends on the left of the figure give the variation in the sensitivity variable from favourable, to planned and to unfavourable. The results show that the highest impact belongs to crude *jatropha curcas* price. For instance, crude *jatropha curcas* with price of $490/ton can decrease the life cycle cost to $452 million which is 23% reduction. However, increasing the price of crude *jatropha curcas* to $910/ton will increase the total life cycle production cost to $715 million. Besides, the discount rate also causes a huge impact on the life cycle cost which is followed by oil conversion yield and operating rate. This implies that improvement of the biodiesel conversion process and lowering the operating rate could reduce biodiesel production cost.

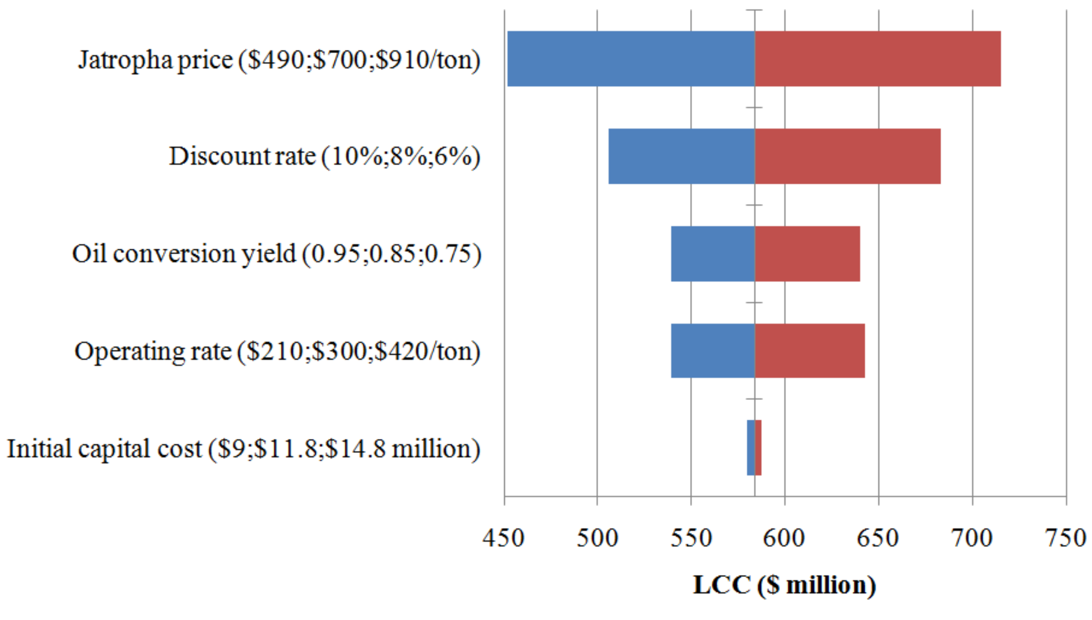

Figure 4.7: Sensitivity analysis of life cycle cost for *jatropha curcas* biodiesel production.

Figure 4.8 shows the sensitivity analysis results of *calophyllum inophyllum* biodiesel production for five input variable. The legends on the left of the figure give the variation in the sensitivity variable from favourable, to planned and to unfavourable. As expected, variation in the price of CBO represents the dominant impact on the life cycle cost; second to this is the present value discount rate. For instance, the crude *calophyllum inophyllum* price of $560/ton reduces the total life cycle production cost to $463 million. However, if the CBO price increases to $1040/ton, the total life cycle production cost will be increased to $745 million. As for discount rate increase to 10% per annum, it causes 13% reduction in total life cycle production cost. Besides, oil conversion yield and operating cost also cause a large impact on *calophyllum inophyllum* biodiesel production. However, the effect of the initial capital cost on biodiesel production cost is small.

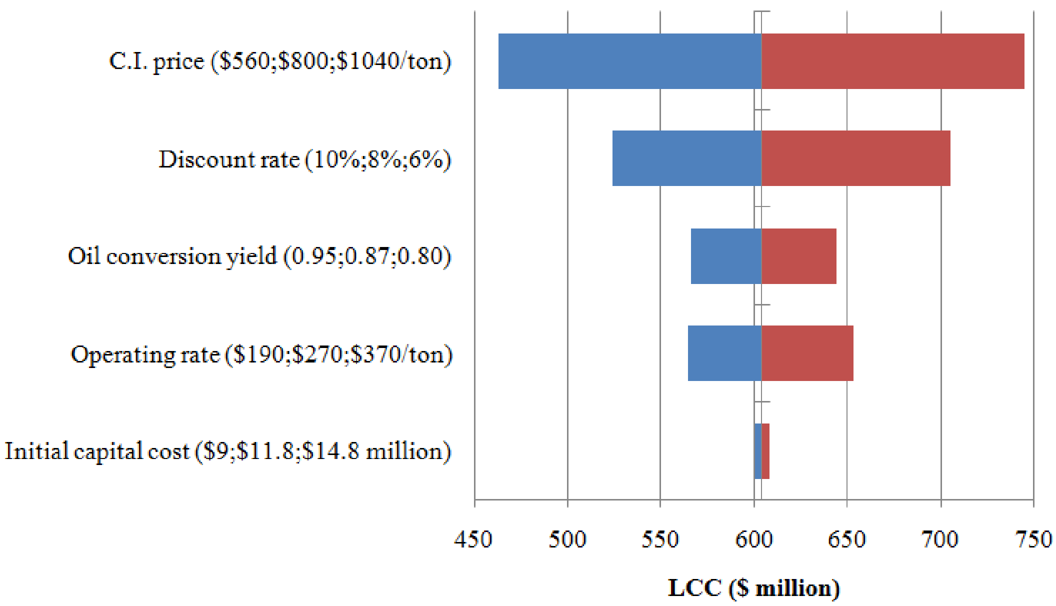

Figure 4.8: Sensitivity analysis of life cycle cost for *calophyllum inophyllum* biodiesel production.

The price of crude palm oil is the key driver of palm biodiesel production. Therefore, the effect of changes in crude palm oil price on biodiesel production cost was further analyzed and the results are shown in Figure 4.9. It can been seen that crude palm oil price has a linear correlation with palm biodiesel production cost; an increase of crude palm oil price by $0.1/kg will cause $0.057/litre rise in biodiesel production cost. The palm biodiesel production cost will be raised to $0.84/litre when the CPO price increases to $1300/ton.

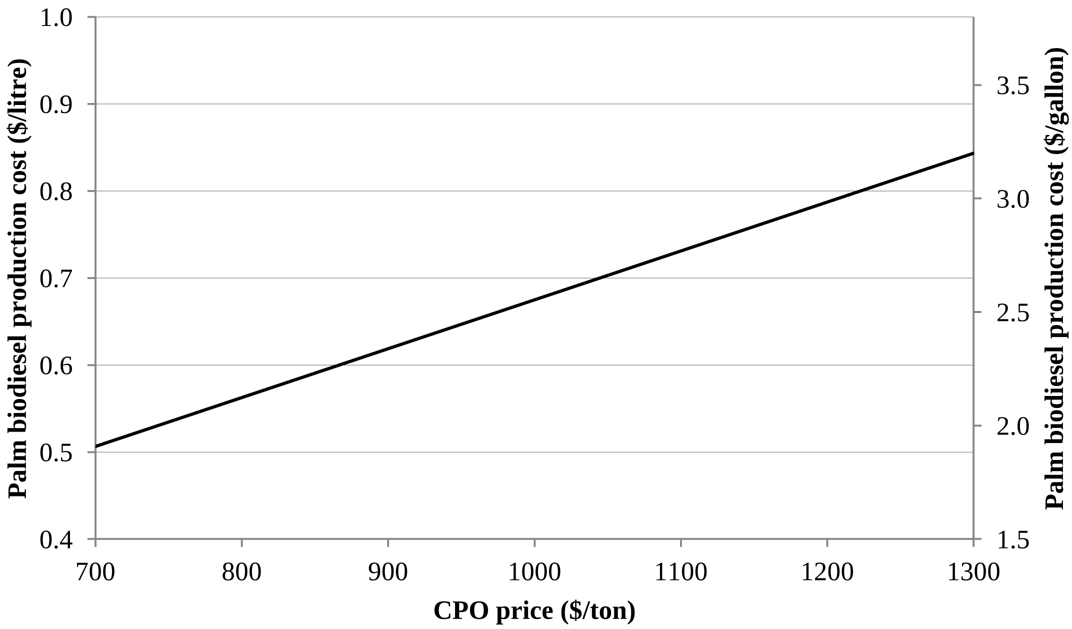

Figure 4.9: The impact of crude palm oil price on the biodiesel production cost.

Figure 4.10 illustrates the effect of the price variation in the crude *jatropha curcas* oil on biodiesel production cost. The crude *jatropha curcas* oil price has a linear correlation with *jatropha curcas* biodiesel production cost. An increase of crude *jatropha curcas* oil price by \$0.1/kg will cause \$0.054/litre rise in biodiesel production cost. In fact, there are 10% changes in *jatropha curcas* production cost for every \$100/ton change in crude *jatropha curcas* oil price. The jatropha production cost can maintain below \$0.40 when the crude *jatropha curcas* oil price fall to \$500/ton.

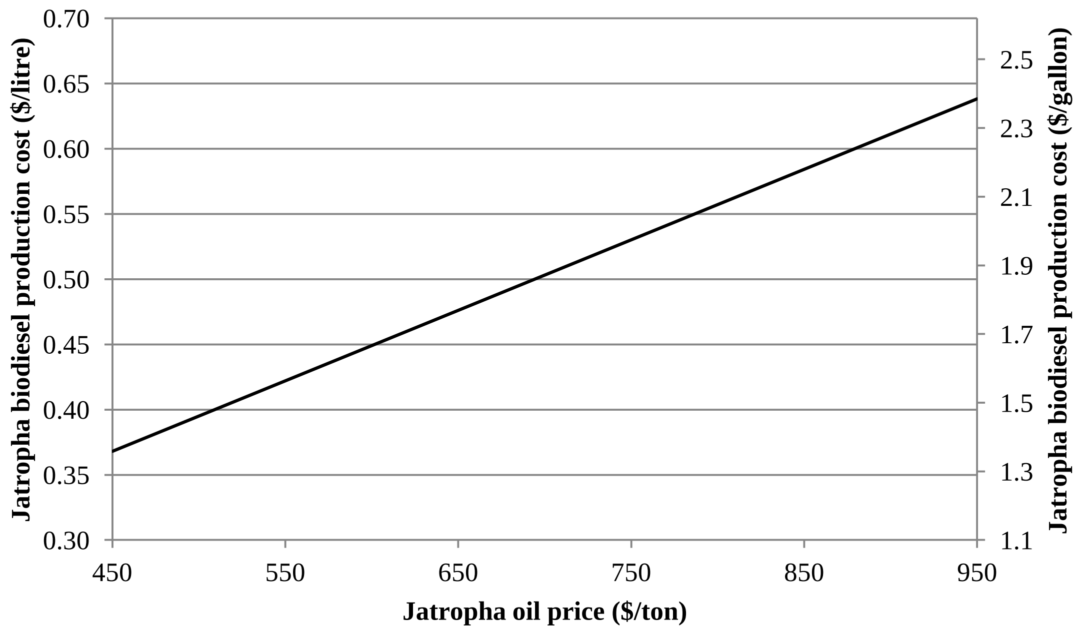

Figure 4.10: The impact of *jatropha curcas* oil price on the biodiesel production cost.

Figure 4.11 shows the effect of changes in crude *calophyllum inophyllum* oil price on the biodiesel production cost. The crude *calophyllum inophyllum* oil price has a linear correlation with *calophyllum inophyllum* biodiesel production cost. When crude *calophyllum inophyllum* oil price increases by \$0.1/kg, it will cause \$0.051/litre rise in biodiesel production cost. The *calophyllum inophyllum* biodiesel production cost will be decreased to \$0.4/litre when the crude *calophyllum inophyllum* oil price is \$550/ton. At this price, it makes *calophyllum inophyllum* biodiesel become competitive with fossil diesel fuel.

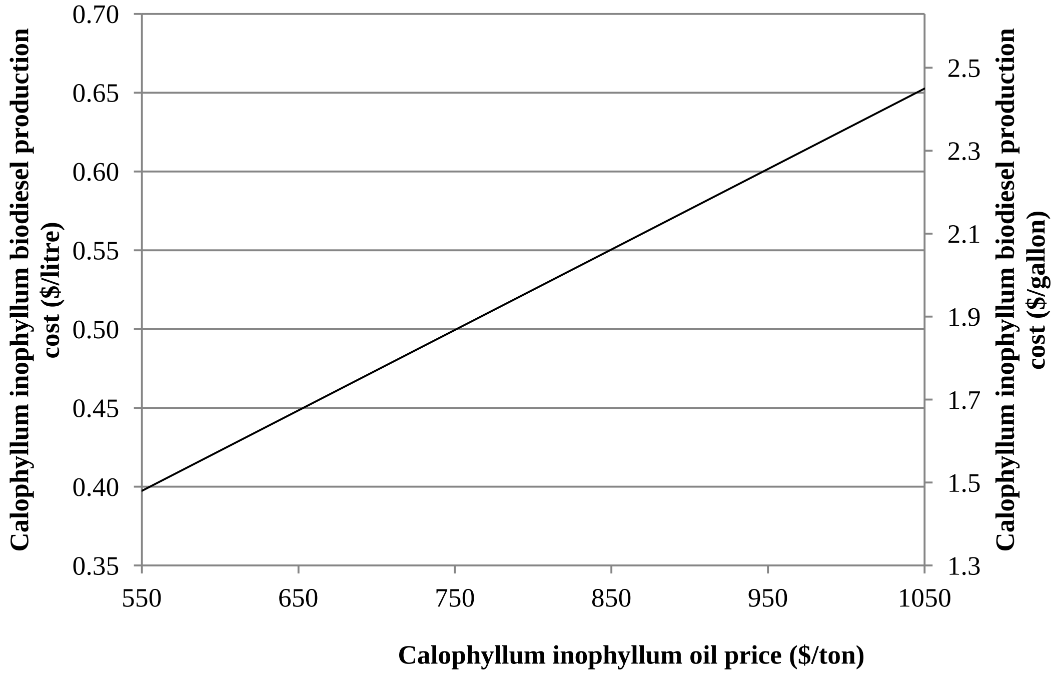

Figure 4.11: The impact of *calophyllum Inophyllum* oil price on the biodiesel production cost.

4.7 Taxation and subsidy scenarios on biodiesel fuel

Taxation and subsidy scenarios are presented for the final biodiesel cost in this section. Final biodiesel cost is the total life cycle cost (biodiesel production cost), distribution cost and profit margin. Total distribution cost and profit margin account to be 10% of biodiesel production cost based on the Eq. 3.29. The considered scenarios are total tax exemption, 15% taxation, subsidy of $0.10/litre and $0.18/litre for biodiesel in comparison with fossil diesel price. The $0.10/litre and $0.18/litre subsidy cost are chosen, based on the current subsidy costs for diesel and petrol fuel in Malaysia. The considered fossil diesel price is based on $0.581/litre retail price of diesel fuel in Malaysia. There is a difference in energy contents between the fossil diesel and biodiesel fuels. Therefore, a fuel consumption substitution ratio of biodiesel to fossil diesel as shown in Eq. 3.31 has been taken into account for calculation.

Table 4.9 shows a comparison of final palm biodiesel price with fossil diesel at different taxation and subsidy scenarios. The results indicate that final palm biodiesel price is much higher than fossil diesel fuel at current production price even considering the tax exemption and subsidies.

Table 4.9: Palm biodiesel taxation and subsidy scenarios at current production cost.

	Palm biodiesel				Fossil Diesel
	Total tax exemption	15% of taxation	subsidy $0.10/litre	subsidy $0.18/litre	
Biodiesel cost ($/litre)	0.739	0.739	0.739	0.739	-
Taxes/Subsidy ($/litre)	-	0.111	0.10	0.18	-
Total ($/litre)	0.739	0.850	0.639	0.559	0.581
Total ($/litre diesel)	0.867	0.997	0.750	0.656	0.581

Table 4.10 presents the comparison of the final *jatropha curcas* biodiesel price with fossil diesel at different taxation and subsidy scenarios. The results show that the price of *jatropha curcas* biodiesel with tax exempted is $0.6/litre which is $0.02 higher than diesel fuel. However, the final biodiesel price is compatible and lower than the fossil diesel price when the subsidy is provided for biodiesel fuel.

Table 4.10: *Jatropha curcas* biodiesel taxation and subsidy scenarios at current production cost.

	Jatropha curcas biodiesel				Fossil Diesel
	Total tax exemption	15% of tax	Subsidy $0.10/litre	Subsidy $0.18/litre	
Biodiesel cost ($/litre)	0.553	0.553	0.553	0.553	-
Taxes/Subsidy ($/litre)	-	0.083	0.10	0.18	-
Total ($/litre)	0.553	0.636	0.453	0.373	0.581
Total cost ($/litre diesel)	0.602	0.692	0.493	0.406	0.581

Table 4.11 shows a comparison of final *calophyllum inophyllum* biodiesel price with fossil diesel at different taxation and subsidy scenarios. It can be seen that the *calophyllum inophyllum* biodiesel price with subsidy of \$0.10/litre and \$0.18/litre are compatible and even lower than the diesel fuel when the CBO price is \$0.7/kg or below.

Table 4.11: *Calophyllum inophyllum* biodiesel taxation and subsidy scenarios at current production cost.

	Calophyllum inophyllum biodiesel				Fossil Diesel
	Total tax exemption	15% of tax	subsidy \$0.10/litre	subsidy \$0.18/litre	
Biodiesel cost (\$/litre)	0.578	0.578	0.578	0.578	-
Taxes/Subsidy (\$/litre)	-	0.087	0.10	0.18	-
Total (\$/litre)	0.578	0.664	0.478	0.398	0.581
Total cost (\$/litre diesel)	0.610	0.702	0.504	0.420	0.581

4.7.1 Taxation and subsidy scenarios at varying feedstock price

Taxation and subsidy scenarios based on final biodiesel cost as a function of crude feedstock price are discussed here. There are four taxation and subsidies scenarios considered which are tax exempted, 15% of taxes, subsidy of \$0.10/litre and \$0.18/litre for biodiesel.

Figure 4.12 shows the taxation and subsidy scenarios of palm oil biodiesel at a function of CPO price. As shown in the figure, the biodiesel is competitive with fossil diesel fuel when the CPO price below \$0.6/kg or \$600/ton with tax exemption. However, when the price of CPO surges up to \$950/ton, the biodiesel price becomes higher than the fossil diesel although \$0.18/litre of subsidy is provided.

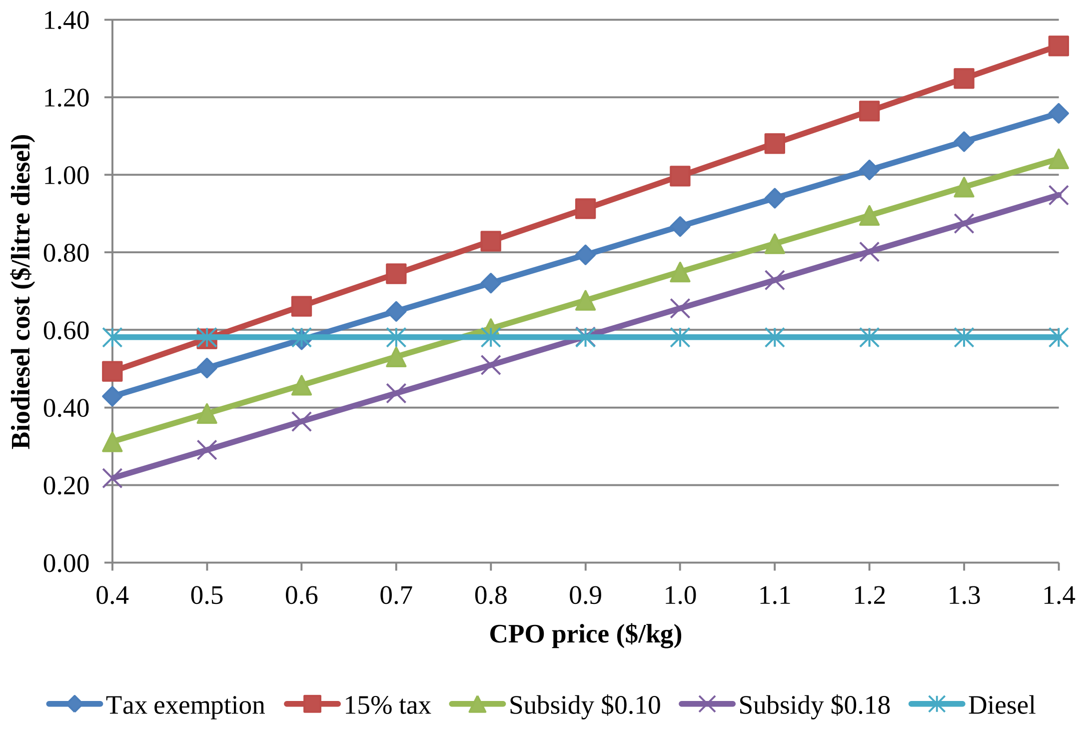

Figure 4.12: Taxation and subsidy scenarios of palm biodiesel on CPO price.

Taxation and subsidy scenarios of *jatropha curcas* biodiesel at varying CJO price are illustrated in Fig. 4.13. The biodiesel is competitive with diesel fuel when the CJO price is below \$0.7/kg with tax exemption. On the other hand, with subsidy for biodiesel of \$0.10 and \$0.18/litre, the CJO price could reach \$0.83/kg and \$0.97/kg respectively in order to preserve the competitiveness with diesel fuel. Apart from that, when the price of CJO is above \$970/ton, the biodiesel price is higher than fossil diesel although \$0.18/litre of subsidy is provided.

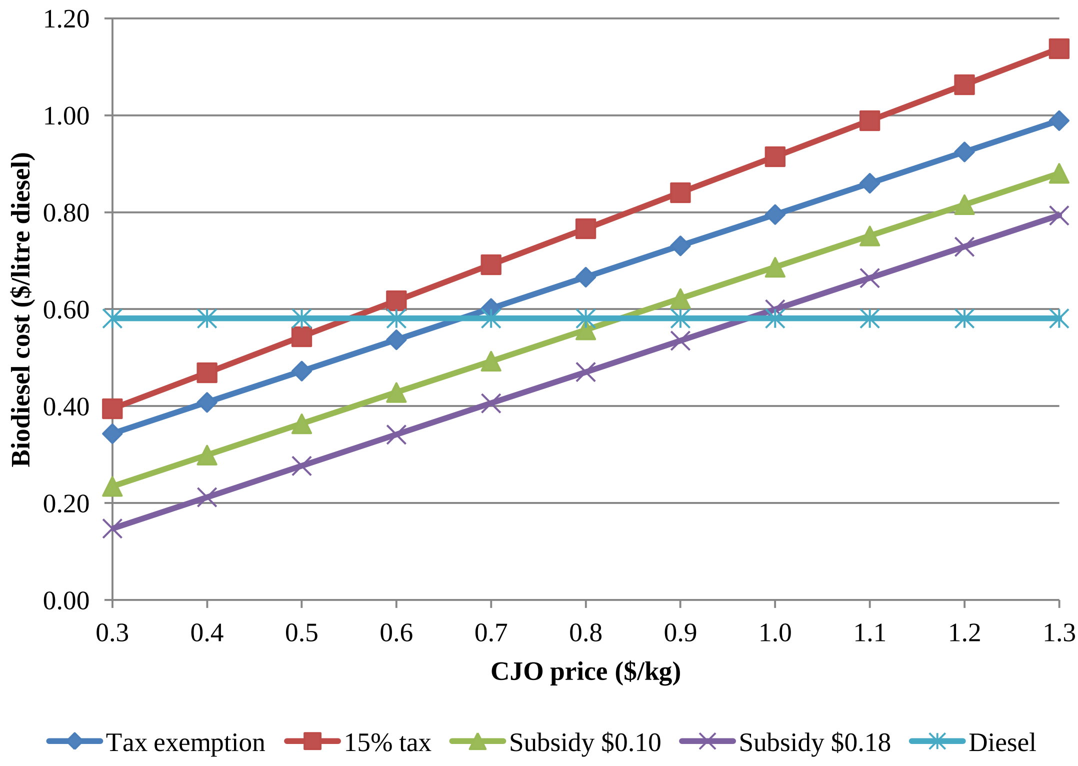

Figure 4.13: Taxation and subsidy scenarios of *jatropha curcas* biodiesel on CJO price.

Figure 4.14 shows the taxation and subsidy scenarios of *calophyllum inophyllum* oil based on the biodiesel cost as a function of CBO price. When the price of CBO is below $750/ton and without giving any direct subsidy, biodiesel fuel is competitive with diesel. However, when the price of CBO surges up to $1.07/kg, the biodiesel price becomes higher than fossil diesel although $0.18/litre of subsidy is provided. On top of that, when the CBO price reaches $1.0/kg, subsidy should be provided in order to preserve the competitiveness of biodiesel with fossil diesel.

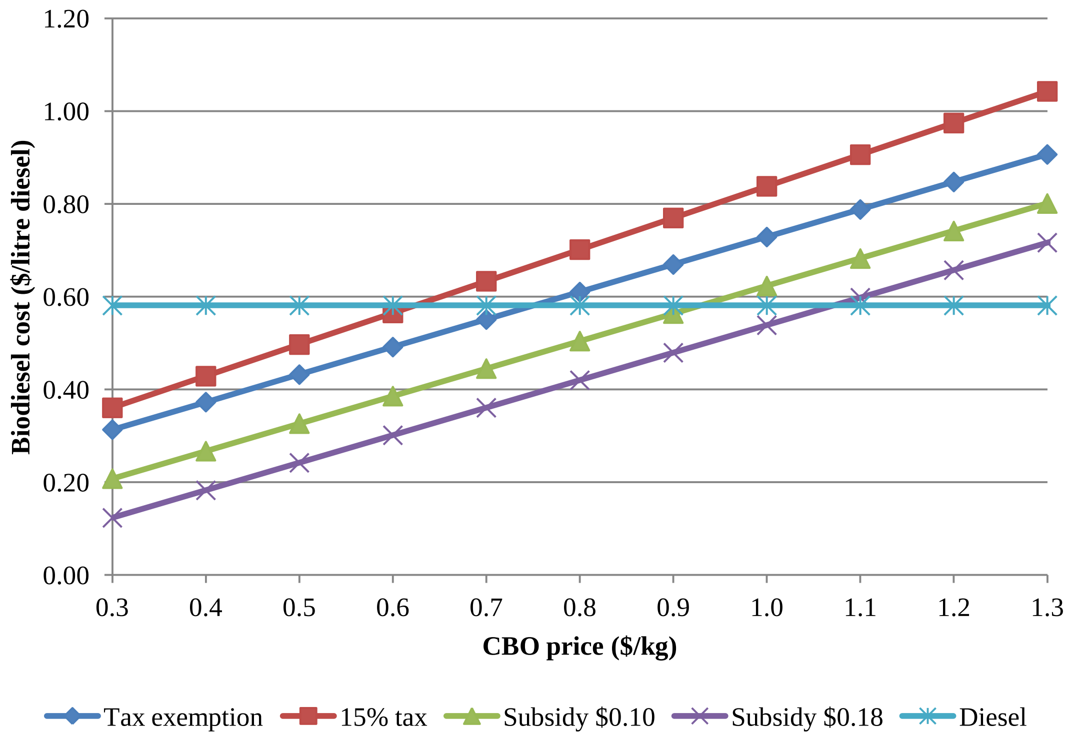

Figure 4.14: Taxation and subsidy scenarios of *calophyllum inophyllum* biodiesel on CBO price.

4.8 Energy and emission impact

The impact of the biodiesel fuel substitution on energy and emission saving is predicted in this section. The calculation results for diesel fuel savings are based on 5% replacement of diesel fuel with palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel. Thus, the energy savings of palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel replacement are presented in Tables 4.12, 4.13 and 4.14 respectively.

The total diesel fuel savings is 337 ktoe in year 2012 and it would increase to 698 ktoe in 2031 when 5% of total diesel consumption substituted by biodiesel in Malaysia. Based on Table 4.12, the required palm oil and palm plantation cropland are reported to be 415 ktoe and 123 thousand hectare in 2012. It is predicted that the required palm biodiesel will increase to 859 ktoe and the cropland needed will rise to 255 thousand hectare in 2031 for 5% of diesel fuel substitution. On the other hand, 377 ktoe of *jatropha* biodiesel with feedstock cropland of 279 thousand hectare are required which is more than double of the palm plantation cropland required in the same year. Moreover, with the same amount of diesel fuel savings, *calophyllum inophyllum* biodiesel only required 90 thousand hectare of cropland to produce 370 ktoe of *calophyllum inophyllum* biodiesel. The required cropland for the *calophyllum inophyllum* biodiesel is about only 70% and 32% of palm and *jatropha curcas* cropland to generate the same amount of energy. The high production rate per hectare of *calophyllum inophyllum* is due to the high oil yield of crude *calophyllum inophyllum* oil which is about 4680 kg/ha.

Table 4.12: Palm biodiesel and cropland needed.

Year	Diesel consumption (ktoe)	Diesel savings (toe)	Biodiesel needed (toe)	Biodiesel needed (litre)	Cropland needed (ha)
2012	6,941	337,130	415,151	472,299,347	123,337
2013	7,263	352,769	434,410	494,209,790	129,058
2014	7,593	368,798	454,148	516,664,593	134,922
2015	7,931	385,215	474,364	539,663,754	140,928
2016	8,276	401,972	494,999	563,139,230	147,059
2017	8,629	419,117	516,113	587,159,064	153,331
2018	8,989	436,603	537,645	611,655,212	159,728
2019	9,357	454,477	559,656	636,695,719	166,267
2020	9,733	472,739	582,145	662,280,585	172,948
2021	10,116	491,342	605,052	688,341,765	179,754
2022	10,507	510,333	628,439	714,947,304	186,702
2023	10,906	529,713	652,303	742,097,201	193,792
2024	11,312	549,433	676,587	769,723,413	201,006
2025	11,726	569,541	701,349	797,893,983	208,363
2026	12,147	589,989	726,529	826,540,868	215,844
2027	12,576	610,826	752,189	855,732,111	223,467
2028	13,013	632,051	778,326	885,467,713	231,232
2029	13,457	653,617	804,882	915,679,629	239,121
2030	13,909	675,571	831,917	946,435,904	247,153
2031	14,368	697,865	859,371	977,668,493	255,309

Table 4.13: *Jatropha curcas* biodiesel and cropland needed.

Year	Diesel consumption (ktoe)	Diesel saving (toe)	Biodiesel needed (toe)	Biodiesel needed (litre)	Cropland needed (ha)
2012	6,941	337,130	377,410	437,830,759	279,253
2013	7,263	352,769	394,919	458,142,170	292,208
2014	7,593	368,798	412,862	478,958,213	305,484
2015	7,931	385,215	431,240	500,278,886	319,083
2016	8,276	401,972	449,999	522,041,112	332,963
2017	8,629	419,117	469,193	544,307,970	347,165
2018	8,989	436,603	488,768	567,016,380	361,649
2019	9,357	454,477	508,778	590,229,421	376,454
2020	9,733	472,739	529,222	613,947,094	391,581
2021	10,116	491,342	550,048	638,106,319	406,990
2022	10,507	510,333	571,308	662,770,175	422,721
2023	10,906	529,713	593,003	687,938,663	438,774
2024	11,312	549,433	615,079	713,548,703	455,108
2025	11,726	569,541	637,590	739,663,374	471,765
2026	12,147	589,989	660,481	766,219,598	488,702
2027	12,576	610,826	683,808	793,280,453	505,962
2028	13,013	632,051	707,569	820,845,940	523,544
2029	13,457	653,617	731,711	848,852,979	541,407
2030	13,909	675,571	756,288	877,364,649	559,592
2031	14,368	697,865	781,246	906,317,871	578,058

Table 4.14: *Calophyllum inophyllum* biodiesel and cropland needed.

Year	Diesel consumption (ktoe)	Diesel saving (toe)	Biodiesel needed (toe)	Biodiesel needed (litre)	Cropland needed (ha)
2012	6,941	337,130	369,727	425,463,137	90,806
2013	7,263	352,769	386,879	445,200,801	95,019
2014	7,593	368,798	404,458	465,428,842	99,336
2015	7,931	385,215	422,462	486,147,261	103,758
2016	8,276	401,972	440,839	507,294,758	108,272
2017	8,629	419,117	459,642	528,932,633	112,890
2018	8,989	436,603	478,819	550,999,587	117,600
2019	9,357	454,477	498,421	573,556,918	122,414
2020	9,733	472,739	518,449	596,604,626	127,333
2021	10,116	491,342	538,851	620,081,413	132,344
2022	10,507	510,333	559,678	644,048,577	137,459
2023	10,906	529,713	580,932	668,506,118	142,679
2024	11,312	549,433	602,558	693,392,739	147,991
2025	11,726	569,541	624,611	718,769,736	153,407
2026	12,147	589,989	647,036	744,575,813	158,915
2027	12,576	610,826	669,888	770,872,267	164,527
2028	13,013	632,051	693,166	797,659,097	170,244
2029	13,457	653,617	716,816	824,875,008	176,053
2030	13,909	675,571	740,893	852,581,295	181,966
2031	14,368	697,865	765,343	880,716,661	187,971

4.8.1 Life cycle emission saving

Evaluating greenhouse gas or CO_2 emissions is required to assess all direct and indirect effects from production to the combustion of biodiesel fuel. Figure 4.15 presents the impact of CO_2 saving from 5% biodiesel substitution for diesel consumption. *Jatropha curcas* biodiesel shows the highest CO_2 saving compare to palm biodiesel and *calophyllum inophyllum* biodiesel. The amount of CO_2 saving for *jatropha curcas* biodiesel is predicted to be around 1200 million kg in year 2031 which is 33% and 40% more than the reported amounts for the palm biodiesel and *calophyllum inophyllum* biodiesel respectively.

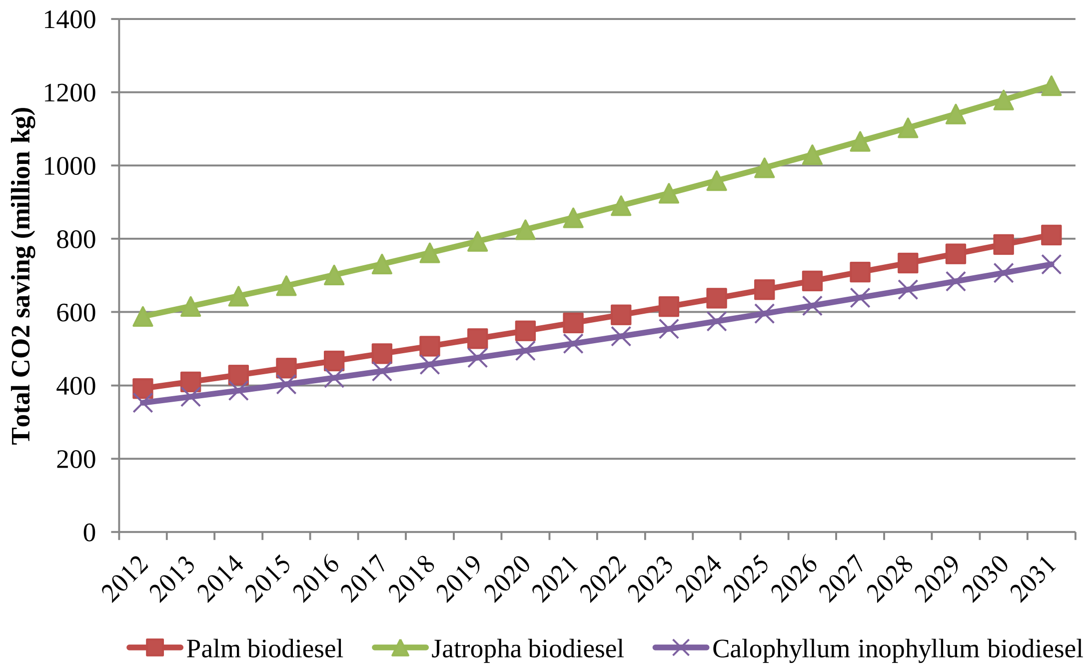

Figure 4.15: Impact of CO_2 saving from 5% biodiesel substitution for diesel consumption.

4.8.2 Ecosystem carbon payback period

Ecosystem carbon payback time is the years required for the biodiesel carbon emission savings from fossil fuel to compensate the carbon losses in ecosystem during land conversion to biodiesel cropland.

Generally, in comparison with fossil diesel fuel, biodiesel shows lower life cycle emission and improvement of environmental performance. However, the extra greenhouse gas emissions loss for natural forest converted to biodiesel cropland is considered as a ‘carbon debt’. It is due to the carbon stock in natural forest which was found to be 3 to 21 times higher than biodiesel cropland plantation (Beer et al., 2007). In order to incorporate the costs of carbon emissions accurately, the greenhouse gas emission reductions must be extended to include the net greenhouse gas emission from land use change. The carbon debt from land clearing can repay over time from life cycle emission saving of biodiesel fuel compare with fossil diesel fuel as shown in Eq. 3.40. Based on the results from this study, it would take around 42 years to payback the carbon debt from converting natural forest to palm biodiesel in Malaysia. For the *jatropha curcas* and *calophyllum inophyllum* biodiesel it would take 70 and 38 years respectively to repay the carbon stock from natural forest. *Calophyllum inophyllum* biodiesel has the lowest payback period compare to the palm and *jatropha* biodiesel due to its high oil yield which is 4680 kg/ha. It can be observed that increasing the feedstock oil yield per ha of biodiesel plantation will reduce the ecosystem carbon payback period. On top of that, after the ecosystem payback period the biodiesel plantation will be a net greenhouse gas reduction source. In contrast, biodiesel plantation can grow on degraded and abandoned croplands which would bring with little or no carbon debt and sustained greenhouse gas advantages.

4.8.3 Potential energy and emission saving of biodiesel

In Malaysia, it is expected that the diesel fuel consumption in the transportation sector will increase to 6,743 ktoe in year 2012. Table 4.15 presents the impact of different potential replacement rates of fossil diesel fuel by palm biodiesel. The potential diesel energy and life cycle CO_2 emission saving are reported to be up to 29 million GJ and 783 million kg respectively for 10% of fossil diesel fuel replacement by palm biodiesel. The total required cropland for oil palm plantation is around 247 thousand hectares when 10% of fossil diesel is replaced by palm biodiesel.

Table 4.15: Impact of cropland, energy and CO_2 saving for palm biodiesel at different replacement rate.

Fossil diesel replacement rate (%)	Fossil diesel replaced (toe)	Biodiesel needed (toe)	Cropland needed (ha)	Diesel energy saving (GJ)	CO_2 saving (Thousand kg)
1	67,426	83,030	24,667	2,906,058	78,308
2	134,852	166,060	49,335	5,812,116	156,615
3	202,278	249,091	74,002	8,718,174	234,923
4	269,704	332,121	98,669	11,624,232	313,230
5	337,130	415,151	123,337	14,530,289	391,538
6	404,556	498,181	148,004	17,436,347	469,846
7	471,982	581,212	172,671	20,342,405	548,153
8	539,407	664,242	197,339	23,248,463	626,461
9	606,833	747,272	222,006	26,154,521	704,768
10	674,259	830,302	246,673	29,060,579	783,076
15	1,011,389	1,245,453	370,010	43,590,868	1,174,614
20	1,348,519	1,660,605	493,347	58,121,158	1,566,152
25	1,685,648	2,075,756	616,683	72,651,447	1,957,690
30	2,022,778	2,490,907	740,020	87,181,736	2,349,228
40	2,697,037	3,321,209	986,693	116,242,315	3,132,304
50	3,371,297	4,151,511	1,233,366	145,302,894	3,915,380

Table 4.16 presents the impact of different potential replacement rates of fossil diesel fuel by *jatropha curcas* biodiesel. The potential life cycle CO_2 emission saving is up to 1,177 million kg and 559 thousand hectares cropland is needed when 10% of fossil diesel fuel is replaced by *jatropha curcas* biodiesel. *Jatropha curcas* biodiesel shows more CO_2 saving compared to the palm biodiesel. However, the cropland required to produce the *jatropha curcas* biodiesel is more than double of palm biodiesel.

Table 4.16: Impact of cropland, energy and CO_2 saving for *jatropha curcas* biodiesel at different replacement rate.

Fossil diesel replacement rate (%)	Fossil diesel replaced (toe)	Biodiesel needed (toe)	Cropland needed (ha)	Diesel energy saving (GJ)	CO_2 saving (Thousand kg)
1	67,426	75,482	55,851	2,906,058	117,676
2	134,852	150,964	111,701	5,812,116	235,351
3	202,278	226,446	167,552	8,718,174	353,027
4	269,704	301,928	223,402	11,624,232	470,702
5	337,130	377,410	279,253	14,530,289	588,378
6	404,556	452,892	335,103	17,436,347	706,053
7	471,982	528,374	390,954	20,342,405	823,729
8	539,407	603,856	446,804	23,248,463	941,404
9	606,833	679,338	502,655	26,154,521	1,059,080
10	674,259	754,820	558,506	29,060,579	1,176,755
15	1,011,389	1,132,230	837,758	43,590,868	1,765,133
20	1,348,519	1,509,640	1,117,011	58,121,158	2,353,510
25	1,685,648	1,887,051	1,396,264	72,651,447	2,941,888
30	2,022,778	2,264,461	1,675,517	87,181,736	3,530,266
40	2,697,037	3,019,281	2,234,022	116,242,315	4,707,021
50	3,371,297	3,774,101	2,792,528	145,302,894	5,883,776

Table 4.17 presents the impact of different potential replacement rates of fossil diesel fuel by *calophyllum inophyllum* biodiesel. The potential saving of the CO_2 emission is 706 million kg and 182 thousand hectares cropland is needed when 10% of fossil diesel fuel is replaced by *calophyllum inophyllum* biodiesel. *Calophyllum inophyllum* biodiesel can save up to 26% and 68.5% of cropland compared to the palm and *jatropha curcas* biodiesel for 10% of diesel replacement rate. The advantage of *calophyllum inophyllum* biodiesel in comparison with palm and *jatropha curcas* biodiesel is being the lowest required cropland. Besides, *calophyllum inophyllum* biodiesel is from non-edible feedstock. Thus, *calophyllum inophyllum* biodiesel has no conflict between food and fuel competition. Furthermore, *calophyllum inophyllum* plant can tolerate various kinds of soil and it can grow in degraded and marginal soil.

Table 4.17: Impact of cropland, energy and CO_2 saving for *calophyllum inophyllum* biodiesel at different replacement rate.

Fossil diesel replacement rate (%)	Fossil diesel replaced (toe)	Biodiesel needed (toe)	Crop land needed (ha)	Diesel energy saving (GJ)	CO_2 saving (Thousand kg)
1	67,426	73,945	18,161	2,906,058	70,578
2	134,852	147,891	36,323	5,812,116	141,155
3	202,278	221,836	54,484	8,718,174	211,733
4	269,704	295,782	72,645	11,624,232	282,310
5	337,130	369,727	90,806	14,530,289	352,888
6	404,556	443,673	108,968	17,436,347	423,465
7	471,982	517,618	127,129	20,342,405	494,043
8	539,407	591,564	145,290	23,248,463	564,621
9	606,833	665,509	163,452	26,154,521	635,198
10	674,259	739,455	181,613	29,060,579	705,776
15	1,011,389	1,109,182	272,419	43,590,868	1,058,664
20	1,348,519	1,478,910	363,226	58,121,158	1,411,552
25	1,685,648	1,848,637	454,032	72,651,447	1,764,439
30	2,022,778	2,218,365	544,839	87,181,736	2,117,327
40	2,697,037	2,957,820	726,451	116,242,315	2,823,103
50	3,371,297	3,697,275	908,064	145,302,894	3,528,879

Diesel production cost

The diesel fuel cost is calculated and estimated by crude petroleum oil price using refining margin of 18% (Energy Information Administration, 2011). The diesel fuel production cost at different crude oil price is calculated by using Eq. 3.30. The results are presented in Figure 4.16. The diesel production cost is \$0.557 when the crude oil price is \$75/barrel.

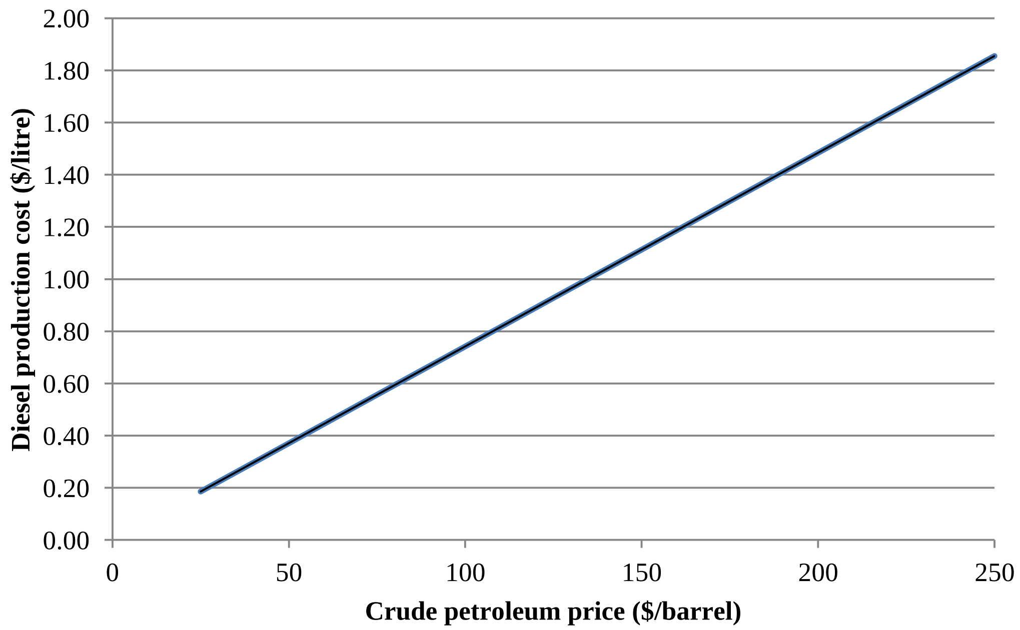

Figure 4.16: Diesel fuel production cost as a function of crude petroleum price.

4.9 Economic impact: biodiesel breakeven cost

Biodiesel breakeven cost is at a point in which price of the biodiesel is economically competitive with the fossil diesel. Biodiesel breakeven cost is calculated based on the comparison between the biodiesel production costs at different crude fossil oil price with diesel production cost. Figures 4.9-4.11 show the biodiesel production cost as a function of crude feedstock cost while the production cost of diesel fuel at different crude petroleum price is illustrated in Figure 4.16. The different energy content of biodiesel and diesel fuel is taken into account. Thus, the cost of biodiesel production is converted to the price per diesel equivalent by considering the substitution ratio as shown in Eq. 3.32. The calculated breakeven price is based on no subsidy assumption for both fuels. By making the comparison from Figure 4.9 and 4.16, when the price of produced biodiesel is at the same price with diesel price, the equivalent cost and crude petroleum cost was the breakeven cost. Therefore, a breakeven graph is derived from the equivalent cost of feedstock and crude petroleum. This means that there are equal price of biodiesel and diesel along the breakeven line. However, the upper part area of the line in Figures 4.17-4.19 represents the subsidy needed for replacement of diesel fuel with palm biodiesel fuel. On the other hand, the lower part of the line area is the potential saving generated by the substitution of biodiesel.

Figures 4.9 and 4.16 indicate that palm biodiesel is likely to be competitive with diesel fuel when the CPO price is $1000/ton and the crude oil price is around $105/barrel or above. At this price, biodiesel and diesel fuel production cost are around $0.8/litre of diesel equivalent. Thus, the breakeven price for palm biodiesel at different petroleum oil and crude palm oil price can be obtained and presented in Figure 4.17. The upper part area of the line in Figure 4.17 represents the subsidy needed for replacement of diesel fuel with palm biodiesel fuel whereas the lower part of the line area is the potential saving generated by the substitution. For instance, when the crude petroleum oil price is

$100/barrel, biodiesel fuel is comparable with diesel fuel at CPO price of $931/ton. When the CPO price increases to above $931/ton, subsidy is required to keep biodiesel viable. However, if the CPO price falls below $931/ton, a saving would be generated by substituting diesel fuel with palm biodiesel fuel.

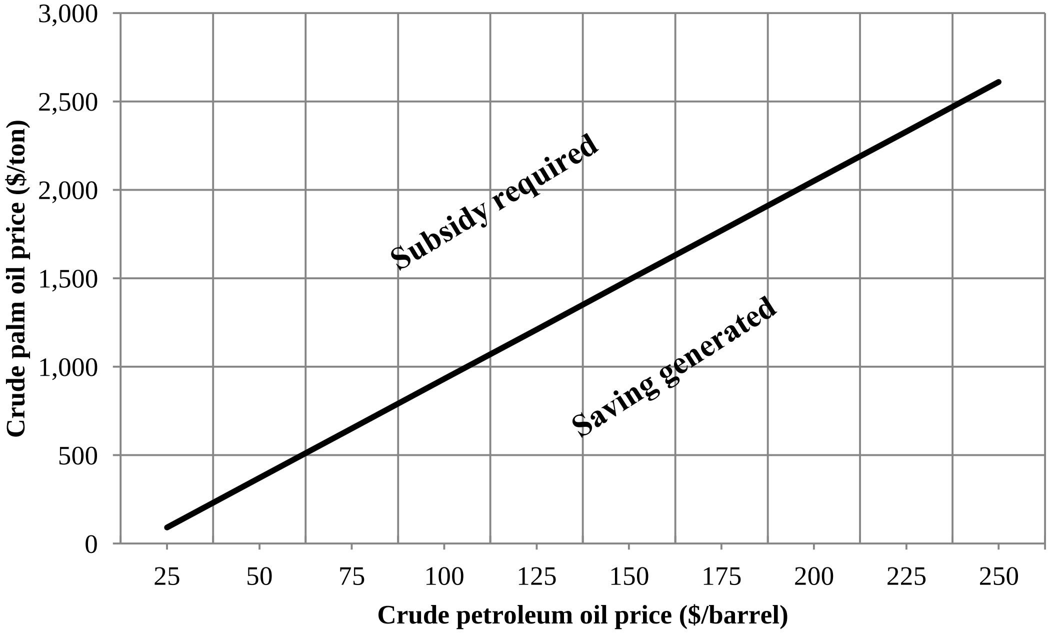

Figure 4.17: Breakeven price for palm biodiesel production at different petroleum and CPO prices.

Figure 4.10 and 4.16 indicate that *jatropha curcas* biodiesel is competitive with diesel fuel when the CJO price is \$800/ton and the crude oil price is around \$80/barrel or above. At this price, both fuel production cost are around \$0.6/litre of diesel equivalent. Based on the method above and the listed data in Figure 4.10 and 4.16, the breakeven price for *jatropha curcas* biodiesel at different petroleum oil and CJO price are calculated and illustrated in Figure 4.18. It is shown that when the crude petroleum oil price is \$80/barrel, *jatropha curcas* biodiesel fuel is comparable with diesel fuel at CJO price of \$780/ton. When the CJO price increases to above \$780/ton, subsidy is needed to keep biodiesel viable at \$80/barrel of crude petroleum. However, if the CJO price falls to \$780/ton or below, a saving would be generated by replacing diesel fuel with *jatropha curcas* biodiesel fuel.

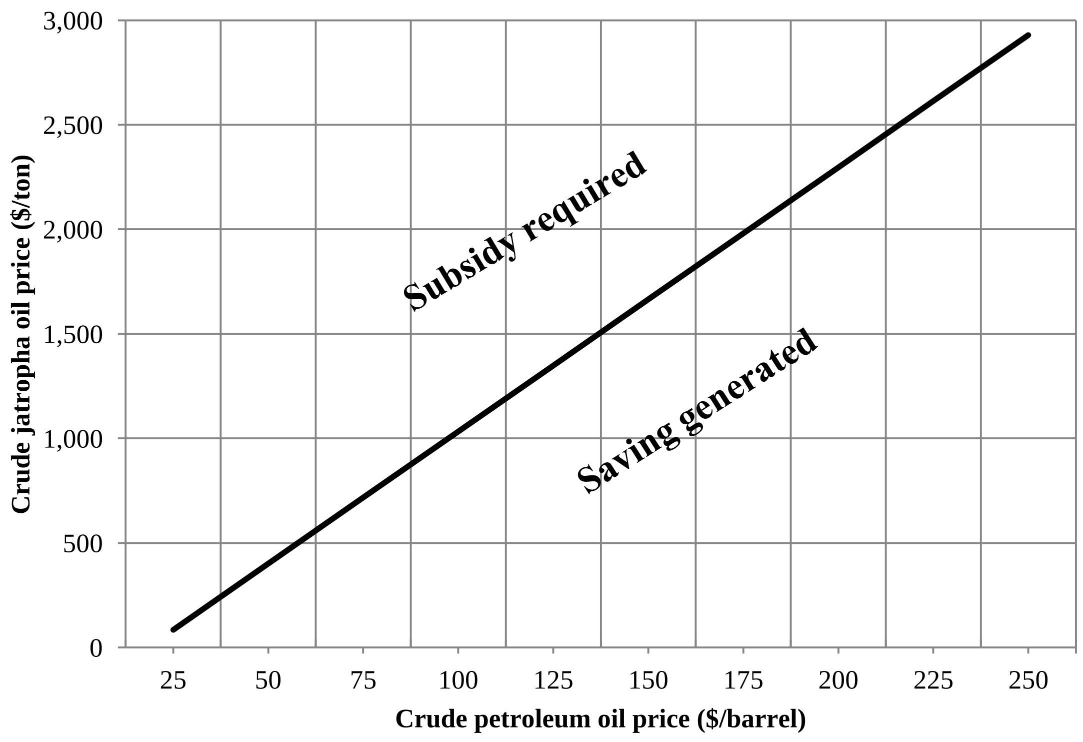

Figure 4.18: Breakeven price for *jatropha curcas* biodiesel production at different petroleum and CJO prices.

Besides, Figures 4.11 and 4.16 indicate that *calophyllum inophyllum* biodiesel is likely to be competitive with diesel fuel when the CBO price is $800/ton and crude oil price is around $75/barrel or above. Biodiesel and diesel fuel production costs are around $0.55/litre of diesel equivalent at this price. The breakeven price for *calophyllum inophyllum* biodiesel at different price of petroleum oil and CBO are presented in Figure 4.19. It can be seen that when the crude petroleum oil price is $80/barrel, biodiesel fuel is comparable with diesel fuel at CBO price of $873/ton. When the CBO price increases to above $873/ton, subsidy is required to keep biodiesel viable. However, when the CBO price falls below $873/ton saving would be generated by substituting diesel fuel with *calophyllum inophyllum* biodiesel fuel at $80/barrel of crude petroleum oil.

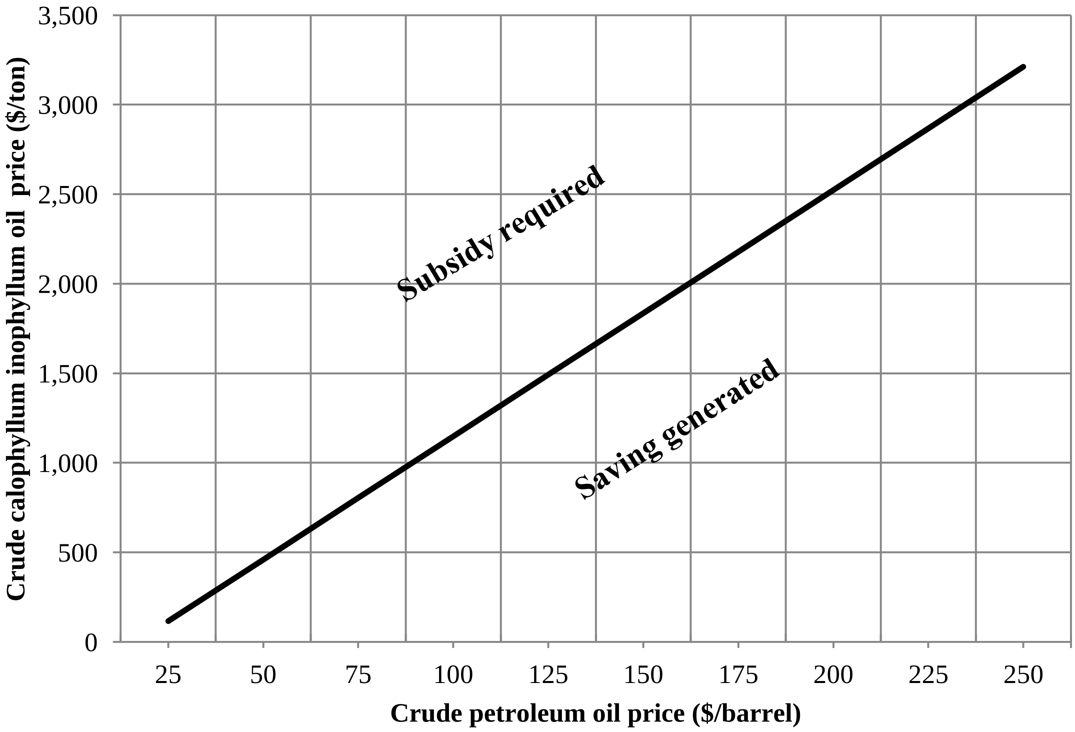

Figure 4.19: Breakeven price for *calophyllum inophyllum* biodiesel production at different petroleum and CBO prices.

4.9.1 Potential cost saving and subsidy costs

Currently, direct subsidies are not provided by the Malaysian government for biodiesel production and consumption or even plantation and production for feedstock oil. In this section, the potential cost saving and subsidy cost for substitution of diesel fuel by biodiesel will be discussed. It is assumed that 5% of total diesel fuel in year 2012 will be replaced by biodiesel fuel which is around 337 ktoe or 403 million litre of diesel fuel. At crude petroleum price of $100/barrel, the diesel production cost is $0.74/litre (Figure 4.16), while CPO price at $1000/ton, the palm biodiesel production cost is $0.79/litre of diesel equivalent (Figure 4.9). As a result, the government needs to provide subsidies or the consumer will bear the cost difference of $0.05/litre between diesel and palm biodiesel. If the government have to provide subsidies to bear the different fuel prices at CPO price of $1000/ton and crude petroleum of $100/barrel, an extra cost of $18 million will be incurred to the government per year when replacing 5% of diesel fuel (337 ktoe of diesel fuel) with palm biodiesel.

Table 4.18 shows the saving and subsidy costs for replacing 5% of diesel fuel with palm biodiesel. The results reveal that the subsidies costs rise with the increasing of CPO price. If the CPO price reaches to $2000/ton and crude petroleum price at $100/barrel, the subsidies cost would be $286 million per year. However, if the CPO price decreases to $400/ton, the biodiesel fuel will be more cost effective than the diesel fuel.

On the other hand, when the crude petroleum prices increase to $200/barrel and the CPO price remains at $1000/ton, around $280 million would be saved for 5% of diesel fuel by replacing palm biodiesel per year. While the crude petroleum price falls to $50/barrel, the extra subsidies will cost around $168 million/year.

Table 4.18: Saving and subsidy costs for replacing 5% of diesel fuel with palm biodiesel ($ millions).

CPO price	Crude petroleum oil price ($/barrel)									
($/ton)	25	50	75	100	125	150	175	200	225	250
400	-82	-8	67	142	217	291	366	441	515	590
600	-136	-61	14	88	163	238	313	387	462	537
800	-189	-114	-40	35	110	184	259	334	409	483
1,000	-243	-168	-93	-18	56	131	206	280	355	430
1,200	-296	-221	-147	-72	3	78	152	227	302	376
1,400	-350	-275	-200	-125	-51	24	99	174	248	323
1,600	-403	-328	-254	-179	-104	-29	45	120	195	270
1,800	-456	-382	-307	-232	-157	-83	-8	67	141	216
2,000	-510	-435	-360	-286	-211	-136	-61	13	88	163

By applying the same method, which is used for palm biodiesel at above section, saving and subsidy costs of replacing 5% of diesel fuel with *jatropha curcas* biodiesel are tabulated in Table 4.19. The results show that the potential saving rises with increasing crude petroleum price or decreasing the CJO price. For example, the CJO price at 800/ton and crude petroleum price at $100/barrel, the annual saving around $55 million will be generated for 5% of diesel fuel replaced by *jatropha curcas* biodiesel. However, when the crude petroleum price rises to $200/barrel and the CJO price remains at $800/ton, around $354 million saving will be generated annually. On top of that, when the CJO price decreases to $400/ton and the crude petroleum price remains at $100/ton, the biodiesel fuel is still more cost effective than the diesel fuel. Apart from that, at higher CJO price and lower crude petroleum price, subsidies are required for *jatropha curcas* biodiesel to preserve the competitiveness with diesel fuel.

Table 4.19: Saving and subsidy costs for replacing 5% of diesel fuel with *jatropha curcas* biodiesel ($ millions).

CJO price	Crude petroleum oil price ($/barrel)									
($/ton)	25	50	75	100	125	150	175	200	225	250
200	-27	47	122	197	272	346	421	496	571	645
400	-75	0	75	150	224	299	374	449	523	598
600	-122	-47	28	102	177	252	326	401	476	551
800	-169	-94	-20	55	130	204	279	354	429	503
1,000	-216	-142	-67	8	82	157	232	307	381	456
1,200	-264	-189	-114	-40	35	110	185	259	334	409
1,400	-311	-236	-162	-87	-12	63	137	212	287	362
1,600	-358	-284	-209	-134	-59	15	90	165	239	314
1,800	-406	-331	-256	-181	-107	-32	43	117	192	267

Table 4.20 shows the saving and subsidy costs of replacing 5% of diesel fuel with *calophyllum inophyllum* biodiesel. Table 4.20 indicated that at crude petroleum price of \$100/barrel and CBO price of \$800/ton, *calophyllum inophyllum* biodiesel fuel will be more economic and cost effective than the diesel fuel. By replacing 5% of diesel fuel with *calophyllum inophyllum,* biodiesel will generate around \$76 million saving per year. Furthermore, with the price of CBO price falls and crude petroleum price increases, then more savings will be generated. However, when CBO price rises to \$1600/ton or crude petroleum price decreases to \$50/barrel, extra subsidies are needed to maintain the competitiveness of *calophyllum inophyllum* biodiesel fuel with diesel fuel.

Table 4.20: Saving and subsidy costs for replacing 5% of diesel fuel with *calophyllum inophyllum* biodiesel (\$ millions).

CBO price	Crude petroleum oil price (\$/barrel)									
(\$/ton)	25	50	75	100	125	150	175	200	225	250
200	-18	56	131	206	281	355	430	505	580	654
400	-62	13	88	162	237	312	387	461	536	611
600	-105	-30	44	119	194	268	343	418	493	567
800	-149	-74	1	76	150	225	300	374	449	524
1,000	-192	-117	-43	32	107	182	256	331	406	480
1,200	-236	-161	-86	-11	63	138	213	288	362	437
1,400	-279	-204	-130	-55	20	95	169	244	319	394
1,600	-322	-248	-173	-98	-24	51	126	201	275	350
1,800	-366	-291	-216	-142	-67	8	82	157	232	307

The results of this study show that the energy used by road transport sector is around 36% of total energy consumption and is increasing with very high growth rate. Currently, the road transport is highly dependent on the petroleum products such as petrol and diesel fuel which is predicted to be depleted in near future. On top of that, road transport also causes serious air pollution by emitting a high level of GHG and CO_2 emissions. And, the number of vehicles and energy consumption from road transport are predicted to increase substantially in the future. Therefore, biodiesel fuel is one of the significant solutions to oil shortages, global warming and air pollution for road vehicles. It is proved that introducing biodiesel policy for road transport will offer great benefits in terms of energy saving, environmental and economic benefits. The projected diesel saving and CO_2 emissions reduction are estimated to be 698 ktoe and 1200 million kg by year 2031 with replacement of 5% diesel fuel with biodiesel. Apart from that, life cycle cost and payback period show that biodiesel production is economically feasible. Therefore, it can attract the investors to invest and develop in this industry. Besides, the price of biodiesel is competitive with diesel fuel when the CJO is $0.7/kg or below. The total subsidies spent for petroleum fuels by the Malaysian government are around $7.8 billion in year 2008. Therefore, savings from subsidy can be generated by using biodiesel fuel when the crude petroleum price is high. As a result, it can reduce the burden of government and taxpayers in subsidizing the petroleum fuel.

In conclusion, since Malaysia is one of the top biodiesel producer countries, it has huge potential and advantage to develop the biodiesel fuel. In order to utilize and implement the biodiesel fuel especially from non-edible feedstock such as *jatropha curcas* and *calophyllum inophyllum* for road transport in Malaysia, the government plays an important role in assistance for research and development.

CHAPTER 5: CONCLUSIONS

5.1 Conclusion

The increasing number of motor vehicles ownership in Malaysia is expected to cause a significant growth in energy consumption and environmental emissions in the future. It is reported that about 36% of total energy use is from the transportation sector and this sector is highly dependent on petroleum products as the source of energy. In order to reduce this growth, biodiesel are become an important alternative fuel for the transportation sector driven by the factors like oil price hikes, the increase of energy security, greenhouse gas emissions and government subsidies. This study has presented the techno-economics analysis of biodiesel production and investigated the feasibility implementation of palm, *jatropha curcas* and *calophyllum inophyllum* oil as biodiesel fuel in Malaysia. Based on the study, the main conclusions of the findings are summarized as below:

The total CO_2 equivalent emission produced by road transport in Malaysia is found to be 67 billion kg. The CO_2 emissions (72%) are the main source of greenhouse gas pollution which is followed by NO_x (20%) emissions. Passenger cars are the main cause of GHG pollutants such as CO_2, CH_4, N_2O, CO, NO_x and NMVOC. This has achieved the first objective of the study.

Biodiesel fuel is being recognized as a solution for diesel fuel in the transportation sector which brings many benefits to environment. Therefore, three potential biodiesels feedstock which are palm oil, *jatropha curcas* and *calophyllum inophyllum* are proposed and reviewed the policy of biodiesel implementation for Malaysia scenarios. These outcomes are in line with the second objective of study which is to propose the use of biodiesel and the implementation of biodiesel policy.

Besides, laboratory experiments are carried out to study the biodiesel production process and biodiesel fuel characteristics. A single step of alkaline catalyst transesterification is used to produce palm oil biodiesel. On the other hand, two step transesterification processes (acid and alkaline catalyzed) are chosen to produce biodiesel for *jatropha curcas* and *calophyllum inophyllum* oil which have high FFA content. Three biodiesel are produced and fulfilled the specification of ASTM D6751 and EN 14214 biodiesel standard. Thus, completed the third objective which is to investigate and carry out the experiment on biodiesel production process for palm, jatropha curcas and calophyllum inophyllum oil.

Furthermore, life cycle cost model and payback period of biodiesel production were developed and evaluated for a lifetime of 20 years. The developed model is flexible as it can be modified and applied for different plant capacity, feedstock, production cost as well as other specific variables. It has been found that the total life cycle cost of palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel is $764, $583 and $604 million respectively by taking into account the glycerine credit over the project lifetime. Payback period for 50 ktoe of palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel production plant was found to be 3.52, 1.90 and 1.98 years respectively. Sensitivity analysis revealed that crude feedstock oil cost is the major contributor of biodiesel production cost. Therefore, the forth objective of the study is achieved.

Finally, the study found that substituting 5% of diesel fuel replaced with *jatropha curcas* biodiesel fuel in road transport can reduce the CO_2 production up to 1200 thousand kg and can save 698 ktoe of diesel fuel in 2031. The carbon debt repaying from land conversion would take around 42, 70 and 38 years for palm, *jatropha curcas* and *calophyllum inophyllum* biodiesel respectively. *Calophyllum inophyllum* biodiesel required the lowest cropland and payback period due to its high oil yield which is 4680kg/ha. The key factor for biodiesel fuel to be competitive with the diesel fuel is due to the fact that the price of crude petroleum is higher coupled with low crude feedstock oil price. These results have achieved the final objective of the study.

As a final note, biodiesel policies and subsidies should be urgently reviewed in order to preserve the goal of energy saving, emissions reduction and economic impact. Therefore, further research and studies on biodiesel production, subsidizing cost and other limitation factors are essential before the wider utilization of biodiesel in Malaysia.

5.2 Recommendation

The study proposed several recommendation to gain an optimum impact of energy saving, emission reduction as well as the economical impact of implementing biodiesel fuel in road transport. The recommendations are summarized as below:

1. A comprehensive life cycle study to assess the energy balance, potential environmental impacts and production cost of the whole process chain from the feedstock production to the biodiesel combustion is recommended for the future studies. It is crucial to figure out the life cycle analysis of cultivation and harvest stage for biofuel's feedstock in order to obtain the energy consumption, emission produced and production cost for this stage as well.
2. Although the biodiesel fuel has been tested in diesel engine but there is still room to improve the energy performance and efficiency. Improving the combustion engine with minor modification would lead to more suitable engine for developed biofuel. Therefore, further research and study on engine testing is recommended in order to improve the energy performance, emission reduction as well as cost efficiency.
3. Biodiesel production can be further improved and optimized by the quality and oil yield of biodiesel. It is recommended to improve the biodiesel production by blending the fuel or through different catalyzed production method. Besides, the two step

transesterification process for high FFA content vegetable oil would increase the cost and time of the production process. It is suggested to carry out further research and development on sophisticated method of biodiesel production in order to achieve cost efficiency and greener process.

4. Implementation of biofuel policy is the responsibility of policymakers, but cooperation and coordination of all agencies such as Malaysian Automotive Association, Malaysia Automotive Institute and Malaysia Energy centre as well as the car manufacturer should be reinforced to increase the synergies in biofuel research and development. Besides, end-users and consumers are one of the crucial factors to make the biofuel implementation successful. Thus, in order to establish the biofuel in road transport, the feedbacks of consumers are also important. Therefore, government should take the initiative to coordinate with correct direction in order to have coherent policy and proactive enforcement of biofuel in the future.

Finally, this study serves as a guideline and starting point towards the implementation of cleaner biofuel for road transport in Malaysia. It is hoped that this thesis can be used as a stepping stone to encourage more researchers and practitioners to be involved in this field to preserve the sustainability of the environment in the future.