TECHNO-ECONOMICS ANALYSIS OF BIODIESEL PRODUCTION FROM NON-EDIBLE REUTEALIS TRISPERMA OIL

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TECHNO-ECONOMICS ANALYSIS OF BIODIESEL PRODUCTION FROM NON-EDIBLE REUTEALIS TRISPERMA OIL

ABSTRACT

The limitation of fossil fuel sources and environmental negative impact persuade scientists around the world to find a solution for this problem. Renewable fuel is one of the possible solutions to replace fossil fuel with cheaper process and can be produced in a short time. The productions of biodiesel from non-edible feedstocks are attracting more attention than in the past. *Reutealis trisperma* known as Philippine Tung is one of the non-edible feedstocks. The seeds contain a high percentage of oil content up to 51%. Thus, *Reutealis trisperma* seeds can be used as feedstock for biodiesel production. Therefore, the focus of this study is to investigate the biodiesel production from crude *Reutealis trisperma* oil using the ultrasonication method through esterification and transesterification process. Followed by, the assessment of the techno-economic and sensitivity analysis of biodiesel production from *Reutealis trisperma* as potential feedstock for biodiesel. Based on the result, the optimum conditions for the esterification and transesterification processes for *Reutealis trisperma* oil, an ultrasonic bath stirrer method with the maximum total power frequency of 40 kHz was used. The esterification process was performed using 2% (v/v) sulfuric acid (H_2SO_4), with a methanol-to-oil molar ratio of 60% (by vol.) at a temperature of 55 °C for 1 hour at 1000 rpm stirring speed. While the optimum condition for the transesterification process with a catalyst of 0.5 wt. % potassium hydroxide (KOH) and methanol-to-oil molar ratio of 60% (by vol.) at a temperature of 60 °C for 1.5 hours with the stirrer speed of 1000 rpm. This optimum condition gives the highest yield of 95.29% for the *Reutealis trisperma* biodiesel. Besides, the results showed that the ultrasonic bath stirrer method had more effect on the reaction time required than using the conventional method. The ultrasonic method reduced half of the conventional method reaction time. The

properties of *Reutealis trisperma* biodiesel fulfilled ASTM D6751 and EN 14214 biodiesel standards which were viscosity: 6.48 mm^2/s, density: 892 kg/m^3, pour point: -2 ^0C, cloud point: -1^0C, flash point: 206.5^0C, calorific value: 40.098 MJ/kg, acid value: 0.26 mg KOH/g. In addition, the life cycle cost and sensitivity analysis of *Reutealis trisperma* biodiesel were also analyzed. It was found that the total life cycle cost for a 50 ktons *Reutealis trisperma* biodiesel production plant with an operating period of 20 years was $710 million, yielding a payback period of 4.34 years. The largest share was the feedstock cost which accounted for 83% of total production cost. The most important finding from this study was that the biodiesel price can compete with fossil diesel if the policy of tax exemptions and subsidies can be fully applied. In conclusion, further research on the limitation of biodiesel production is recommended to be carried out before the biodiesel can be applied in internal combustion engine.

Keywords: Biodiesel; non-edible oil; *Reutealis trisperma*; life cycle cost; biofuel economy

ANALISIS TEKNO-EKONOMIK DARIPADA PRODUKSI BIODIESEL DARI MINYAK TIDAK BOLEH DIMAKAN REUTEALIS TRISPERMA

ABSTRAK

Sumber bahan api fosil dan kesan negatif alam sekitar memujuk ahli sains di seluruh dunia untuk mencari penyelesaian bagi masalah ini. Bahan api yang terbaharukan adalah salah satu penyelesaian yang mungkin untuk menggantikan bahan api fosil dengan proses yang murah dan boleh dihasilkan dalam masa yang singkat. Pembuatan biodiesel daripada bahan minyak mentah tidak dapat dimakan yang menarik perhatian yang lebih daripada di masa lalu. *Reutealis trisperma* dikenali sebagai Filipina Tung adalah salah satu bahan makanan yang tidak boleh dimakan. Benih mengandungi peratusan minyak yang tinggi sehingga 51 % daripada kandungan minyak. Berdasarkan eksperimen jelas benih *Reutealis trisperma* boleh digunakan sebagai bahan mentah bagi pembuatan biodiesel. Oleh kerana itu, fokus kajian ini adalah untuk menyiasat pembuatan biodiesel daripada minyak mentah *Reutealis trisperma* menggunakan kaedah pengaduk ultrasonik melalui proses pengesteran dan transesterifikasi dan menganalisis tekno-ekonomi dan sensitivity daripada pembuatan biodiesel *Reutealis trisperma* sebagai potensi bahan api biodisel. Berdasarkan keputusan itu, keadaan optimum untuk pengesteran dan transesterifikasi minyak *Reutealis trisperma* adalah pada 150 minit dengan menggunakan kaedah pengaduk ultrasonik: pada suhu 55 ^{0}C untuk pengesteran dan pada 60 ^{0}C untuk transesterifikasi: 2 %(v/v) asid sulfurik dan pemangkin sulfurik kepekatan 0.5 wt.%: nisbah metanol-minyak 60 % dan pergolakan kelajuan 1000 rpm. Keadaan optimum memberikan hasil yang paling tinggi adalah 95,29 % bagi biodiesel *Reutealis trisperma*. Keputusan menunjukkan bahawa kaedah pengaduk ultrasonik mempunyai lebih banyak kesan ke atas masa tindak balas yang diperlukan daripada menggunakan kaedah pengaduk konvensional. Kaedah ultrasonik mengurangkan separuh masa daripada kaedah konvensional. Sifat-sifat biodiesel

Reutealis trisperma adalah; ketumpatan; 892 kg/m^3, tuangkan titik; -2 ^{0}C, titik awan; -1 ^{0}C, takat kilat; 206.5 ^{0}C, nilai kalori; 40,098 MJ/kg, nilai asid; 0.26 mg KOH/g mengikut piawaian D6751 ASTM dan EN 14214 biodiesel. Di samping itu, kos kitaran hidup dan analisis sensitivity dari *Reutealis trisperma* biodiesel telah dikira. Ia telah mendapati bahawa jumlah kos kitaran hidup untuk kilang sebesar 50 ktons untuk pembuatan *Reutealis trisperma* biodiesel dengan tempoh operasi 20 tahun adalah $ 710 juta, menghasilkan tempoh bayaran balik selama 4.34 tahun. Bahagian terbesar adalah kos bahan mentah yang mencakupi 83 % daripada jumlah kos pengeluaran. Penemuan paling penting daripada kajian ini ialah bahawa harga biodiesel dari *Reutealis trisperma* ini boleh bersaing dengan diesel fosil jika dasar pengecualian cukai dan subsidi boleh digunakan sepenuhnya. Kesimpulannya, kajian lanjut mengenai had-had pada pembuatan biodiesel adalah perlu sebelum penggunaan biodiesel digunakan dalam enjin pembakaran dalam.

Kata kunci: Biodiesel; minyak tidak boleh dimakan; *Reutealis trisperma*; kos kitaran hidup; ekonomi biofuel

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Description
EN	European standard
ASTM	American Society for Testing and Materials
CRTO	Crude *Reutealis trisperma* oil
CCIO	Crude *Calophyllum inophyllum* oil
CCPO	Crude *Ceiba pentandra* oil
CSFO	Crude *Sterculia foetida* oil
RTME	*Reutealis trisperma* methyl ester
CIME	*Calophyllum inophyllum* methyl ester
CPME	*Ceiba pentandra* methyl ester
SFME	*Sterculia foetida* methyl ester
BC	Biodiesel needed (tons)
BCC	Carbon stock for biodiesel cropland (ton/ha)
BFP	Biodiesel fuel price ($/liter)
BP	By-product credit ($)
CC	Capital cost ($)
CLR	Cropland required (ha)
CPP	Carbon payback period (year)
CPW	Compound present worth factor ($)
DR	Diesel Replacement (tons)
EC	Energy content of diesel fuel (GJ/ton)
EFB	Life cycle emission factor by biodiesel fuel (kg/GJ)
EFD	Life cycle emission factor by diesel fuel (kg/GJ)
EY	Ethanol yield (kg/ha)
FBC	Final biodiesel unit cost ($/liter)

FC	Feedstock cost ($)
FP	Feedstock price ($)
FU	Feedstock consumption (tons)
GC	Diesel consumption (tons)
GCF	Glycerol Conversion Factor ($)
GP	Glycerol Price ($)
GR	Diesel replacement (tons)
HVB	Heating value of biodiesel fuel (MJ/kg)
HVG	Heating value of diesel fuel (MJ/kg)
I	Project year (year)
LCC	Life cycle cost ($)
LSC	Carbon stock for natural forest (ton/ha)
MC	Maintenance cost ($)
MR	Maintenance rate (%)
N	Project life time (year)
η	Fossil diesel replacement rate (%)
OC	Operating cost ($)
OR	Operating rate ($/ton)
OY	Oil yield of biodiesel feedstock (kg/ha)
PC	Annual biodiesel production capacity (tons/year)
PP	Payback Period (year)
P	Density (kg/m^3)
R	Discount rate (%)
RC	Replacement cost ($)
SR	Substitution ratio of biodiesel to diesel fuel (%)
SV	Salvage value ($)

TAX	Annual total tax ($/year)
TBS	Annual total biodiesel sales ($/year)
TCB	Total carbon emitter by biodiesel fuel (kg)
TCD	Total carbon emitter by diesel fuel (kg)
TCS	Total carbon saving (tons)
TDS	Total diesel energy saving (GJ)
TPC	Annual total production cost ($/year)
TR	Tax ratio (%)
$	All monetary unit is in US dollar

CHAPTER 1: INTRODUCTION

1.1. Background

The energy crisis and high fuel demand as well as the depletion of non-renewable sources of raw materials in the world such as fossil fuel have caused public concern about the world's energy needs. Thus, this fuel scenario raised interest among researchers to seek solutions from alternative fuels. Vegetable oil and its derivatives are among the raw materials for alternative fuel production are very attractive and promising. Rudolph Diesel was the first person to use vegetable oil of peanut oil as a fuel mixture on his compression ignition engine. The use of palm oil, soybean oil, peanut oil, rapeseed oil, and sunflower oil had been experimented. The use of vegetable oil for the long term caused oil thickening in the crankcase and injector coking which resulted the piston ring to stick out. Therefore, vegetable oil resistance issues have cause vegetable oil to be less suitable for long-term use if no modifications are made (Karak, 2012; Rakopoulos et al., 2006). To solve this issue, various processing methods to treat vegetable oils have been performed such as esterification-transesterification, micro-emulsion formation and the use of viscosity reduction. Of all the methods that have been experimented, esterification-transesterification is one of the most suitable modifications because the physicochemical properties of esterification-transesterification results are similar to that of diesel fuel. Through the esterification and transesterification process, fatty acids within vegetable oil are converted into alkyl esters (Ong et al., 2013a; Van Gerpen & He, 2014). The ester oil extracted from a transesterification process is called biodiesel. Biodiesel is defined as a mixture of long chain of fatty acids called mono-alkyl esters derived from vegetable oils and alcohols with or without catalysts. Biodiesel is an alternative fuel that uses renewable feedstocks as main raw materials. It is environmentally friendly, portable, non-toxic and readily available in nature (Aditiya et al., 2015; Agarwal, 2007).

Uncertainty of current world oil market price makes biodiesel fuel an attractive option to fulfill the world's energy demand. Applying and increasing the amount of biodiesel usage can help to free up the countries that have been dependent on crude oil reservation such as Nigeria (Alamu et al., 2007). In addition, according to a recent report, fossil fuels began to be limited. Although biodiesel cannot replace diesel fuel completely, biodiesel stands as an alternative fuel has the ability to reduce dependence on fossil fuels and can be used as an additive for diesel fuel in order to improve diesel properties. Use of biodiesel also can reduce the world's pollution because biodiesel produces much less emissions and it is cleaner than diesel fuel derived from petroleum. Biodiesel carbon monoxide levels are lower than diesel fuels because biodiesel is an oxygen fuel, but the NO_X (nitrogen oxide emissions) of biodiesel is higher than diesel fuel (Lapuerta et al., 2008; Xue et al., 2011). The problem of increasing emission in NOx is still being studied. The cold flow property of biodiesel is one of the problems with fuel derived from vegetable oil. Pure biodiesel from non-edible oil has a low pour point (Moser, 2014; Rajasekar & Selvi, 2014; Soriano Jr et al., 2006; Varatharajan & Cheralathan, 2013). In countries with colder climates, the use of biodiesel can lead to blockage of fuel lines and filter blockage because it is easy to crystallize at low temperatures. Therefore, biodiesel has to be blended with diesel fuel (Kwanchareon et al., 2007; Shahir et al., 2014).

There are different types of feedstocks that can be used to produce biodiesel from animal fat or vegetable oils that are environment-friendly. Recently, the use of vegetable oil or first-generation feedstock has gained negative criticism of researchers from around the world due to the conflicting issue of food versus biodiesel which threatens food security in developing countries. Hence, researchers have turned their attention to second-generation feedstocks or non-edible vegetable oils in order to avoid conflicts of food-stuffs with the feedstocks for biodiesel production. In fact, it has been

found that the non-edible vegetable oils have been very promising in terms of its physicochemical properties that are environment-friendly and its availability in nature for the production of biodiesel in a sustainable manner. There are several examples of grain crops from non-edible sources that have been investigated including *Calophyllum inophyllum, Pongamia glabra (koroch seed), Jatropha curcas, Eruca sativa. L, ruberseed, Pongamia pinnata (karanja), Nicotiana tabacum (tobacco), Sterculia feotida, Azadirachta indica (neem), Madhuca indica (mahua), soap nut, milkweed (ascelepias), Guizotia abyssinica, syagrus, tung, Idesia polycarpa var. vestita, algae* (Azam, 2005; Balat, 2010; de La Salles, 2010; Devan, 2009; Hebbal, 2006; Hosamani, 2009; Kansedo, 2009; Knothe, 2009; Liu, 2009; Sahoo, 2007; Sarin, 2009, 2010; Sarma, 2005; Shang, 2010; Sharma, 2010; Silitonga et al., 2016a; Silitonga et al., 2016b; Singh, 2010; Yang, 2009). In addition, recent researches also present that the third-generation feedstocks of microalgae have tremendous potential for biodiesel production. Mata et al. reported that microalgae species are very economical compared with vegetable oil feedstocks and have a higher oil extraction among the other oil crops (Mata, 2010). Microalgae can produce up to 121,104 kg of biodiesel per year with land 0.1 m^2 per kg, which can produce oil at least 70% by weight of dry biomass. Because of the high potential of production values with minimal land needed, microalgae has been presented as a source of great potential for the production of biodiesel, which is currently still dominated by palm oil (Ahmad, 2011). Another source of feedstocks with an economic potential for the biodiesel production is cooking oil. The biodiesel production cost from cooking oil source is very economical when compared to the fresh vegetable oil (Demirbas, 2009b; Math, 2010). It is believed that the production of biodiesel should not rely on one source of feedstock due to the inadequate availability of feedstock resources in the long term. Dependency on fossil fuels in today's world is a perfect example. Hence, the more varieties of feedstocks available around the world for

biodiesel production, that will be the better. Variations in feedstocks for biodiesel from non-edible vegetable oil usually depends on the geographical location of these countries (Kansedo, 2009).

In the biodiesel production process, there are various methods that can be used such as conventional, ultrasound-assisted, non-catalytic supercritical, ultrasonic and microwave methods. Among these methods, ultrasonic and conventional are more preferable and widely studied by using variety raw materials. In many cases, the conventional method is preferred because it is easy to use and simple, while on the other hand the ultrasonic method offers advantages due to its short processing time (Takase et al., 2014). Georgogiani et al. (2008) reported that using ultrasonic methods for processing sunflower seed oil and using ethanol as chemicals can produce biodiesel with ester yields as high as 98% in 40 minutes of reaction time. By using conventional methods, lower yield (88%) was achieved even after 4 hours of reaction time (Georgogianni et al., 2008). Furthermore, Takase et al. (2014) has investigated biodiesel production from crude *Silybum marianum* oil by using conventional and ultrasonic-assisted method. He found that the highest yield was 95.75% using ultrasonication transesterification after 20 minutes of reaction time (Takase et al., 2014). In addition, the biodiesel production from waste fish oil (WFO) has been studied by Maghami et al. (2015) using conventional transesterification and ultrasonication method. The result showed that the highest yield: 87% was achieved in 30 minutes of reaction time by using the ultrasonication method, whereas using conventional methods, it took 1 hour to get the same result as ultrasonication (Maghami et al., 2015). In the literature, ultrasonication proves to provide many advantages in shortening the reaction time, reaction temperature, the amount of catalyst and alcohol required in the experimental process. Based on that, the ultrasonication method could be one of the solutions to reduce the

production time and costs for the process of biodiesel production (Babajide et al., 2010; Gole & Gogate, 2013; Kumar et al., 2010; Singh et al., 2007).

1.2. Problem statement

The only type of biodiesel that is commercially used in Malaysia is palm oil blended with diesel fuel. Since 1970s, the global palm oil production has increased significantly and still it is dominating the world's vegetable oil market. Consequently, the share of palm oil has been doubled in the last twenty years. Indonesia and Malaysia dominate 90% of global palm oil production (Husnawan et al., 2011; Silitonga et al., 2013c). After noticing the tremendous revenue that oil palm could bring to the global market, the Malaysian government is developing ambitious policies regarding biofuel to create a new export industry and increase energy security from this source. Besides that, the country is seeking for improvement in air quality through the use of biodiesel without the worry of the environmental effect such as deforestation and extinction of biodiversity. Oil palm tree (*Elaeis Guineensis)*, a native West Africa plantation, was introduced in the Malaya in early 1870s by British colony. The first commercial planting took place in the Tennamaran estate in 1917 with the seed imported from Indonesia. After 1960, Malaysia government saw the prospect of palm oil and boosted the palm oil expansion, although it was not originally intended for biodiesel production at that time (Lopez & Laan, 2008). However, in this country biodiesel has not been fully applied large-scale utilization and commercialization as a fuel for transportation use. Beside technical factors, there are many non-technical factors affecting the inhibition of the use of biodiesel fuel from application such as production costs, conflict issues of food biodiesel feedstocks, limited land for plantation, crude oil prices, raw material prices, subsidies and issue on taxation policy. In addition, the high production cost of biodiesel compared to fossil fuels is the main cause of constraints in commercializing the biodiesel (Yusuf et al., 2011). The biodiesel production study through

transesterification process, emissions and performance of biodiesel-based engines as fuel has been widely practiced throughout the world including Malaysia. However, the research on the investigation of the feasibility of biodiesel from non-edible *Reutealis trisperma* oil and the techno-economic analysis carried very limited information available in the literature on the production of biodiesel from *Reutealis trisperma*, despite its abundance in the Southeast Asian region. There are several criteria that are necessary to be utilized and developed as biodiesel fuel such as crude oil prices, biodiesel fuel prices, fossil fuel prices, economic impacts, land required, subsidies and environmental impacts. Each country has different criteria, it can't be used as benchmarks for all countries. Therefore, this study focuses on the feasibility of biodiesel production from *Reutealis trisperma* crude oil as well as life cycle costs and sensitivity analysis of *Reutealis trisperma* biodiesel in Malaysia.

1.3. Objective of the study

The main objectives of this study are to assess the feasibility of *Reutealis trisperma* crude oil as one of the biodiesel feedstocks in Malaysia derived from non-edible oil through the biodiesel production process. Furthermore, the study continued with the development of life cycle cost model for the biodiesel production engineering process from *Reutealis trisperma* oil as well as analysis of payback period and sensitivity analysis. The main objectives of the study are as follows:

- To investigate the feasibility of biodiesel production process from crude *Reutealis trisperma* oil using the ultrasonication transesterification method.
- To analyze the characteristics of fuel properties of *Reutealis trisperma* biodiesel according to ASTM D6751 and EN 14214 standards.
- To analyze the life cycle cost and sensitivity analysis of *Reutealis trisperma* biodiesel production in Malaysia.

1.4. Thesis outline

This thesis presents the production of biodiesel from crude oil *Reutealis trisperma* and techno-economic analysis of *Reutealis trisperma* biodiesel in Malaysia. This thesis is divided into five chapters as shown below:

Chapter 1 is an introduction to the research background, objectives and thesis outline.

Chapter 2 presents the literature review consisting of several sources of crude non-edible oil and previous studies of the biodiesel production and physicochemical properties standards. Overviews of techno-economic analysis of the various sources of feedstocks in previous studies have been conducted in several countries. This study also conducted a comprehensive review related to similar study based on articles, reviewed journals, research reports, conference papers, books and others.

Chapter 3 provides the research methodology that consists of biodiesel production process, methods to conduct life cycle cost, potential fuel saving, sensitivity analysis, methods to analyze the taxation and subsidy scenarios of fuels and potential environmental impact.

Chapter 4 describes the results from methodology are carried out during the study. In this section the results of laboratory experiments to produce biodiesel, life cycle costs, the cost of subsidies, the potential fuel savings and emissions reductions, and impacts on the environment are calculated and presented herein.

Chapter 5 is the conclusion achieved in the study and the recommendations that can be done for the future work which will be summarized in this chapter.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

The diminishing supply of fossil fuel reserves and increasing environmental problems associated with the burning of fossil fuel have made renewable energies very promising as future alternative energy sources (Demirbas, 2009b). Among the renewable energies, biodiesel has been touted as one of the most important renewable energy sources, especially in the context of Malaysia (Atabani et al., 2012; Shamsuddin, 2012). Agarwal and Das (2001) conducted experiments to investigate the benefits of mixing biodiesel with petrol diesel fuel, with one-cylinder diesel engines using a wide range of biodiesel blends from linseed oil and conclusive results were obtained showing that a mixture of B20 (Biodiesel 20%) produces the optimum thermal efficiency and emissions of the engine (Agarwal & Das, 2001). In other studies, it has been shown that 10% biodiesel blend of non-edible oils; *Jatropha curcas*, *Ceiba pentandra* and *Calophyllum inophyllum* provides the best engine performance in terms of thermal efficiency, engine power, engine torque, and fuel consumption in a Compression ignition (CI) engine (Ong et al., 2014b). These studies served to demonstrate the huge potential of biodiesel to supplement or even replace fossil diesel fuel, without requiring engine modifications or experiencing deterioration in engine performance. Furthermore, the use of biodiesel can extend the life of the diesel engine; due to its better lubricating properties as compared to diesel fuel (Demirbas, 2007).

The production of biodiesel from feedstocks may be achieved by using different techniques such as direct/blends (Boehman, 2005), micro-emulsion (Ramadhas et al., 2004), pyrolysis (Brennan & Owende, 2010; Naik et al., 2010) and transesterification (Leung et al., 2010; Salahi et al., 2010) with the catalytic transesterification process being the most commonly adopted technique for production (Atadashi et al., 2013).

Commonly, homogeneous catalysts such as Sodium Hydroxide (NaOH) and Potassium Hydroxide (KOH) are used. In recent years, the use of new heterogeneous catalysts in transesterification processes has become an interesting option for researchers. The references (Birla et al., 2012; Dehkordi & Ghasemi, 2012; Liu et al., 2010; Pukale et al., 2015; Tan et al., 2015; Torres-Rodríguez et al., 2016) addressed the use of different heterogeneous catalysts for the production of biodiesel using different feedstocks. Liu et al. (2010) investigated biodiesel production from *Jatropha* oil using nanometer magnetic base catalysts and have shown that 95–99% biodiesel yield was achievable under optimal conditions. These studies have demonstrated that the use of heterogeneous catalysts reduced the effects of using low quality feedstocks, whilst providing high biodiesel yields under optimal conditions (Liu et al., 2010). Another interesting technique for biodiesel production is through catalyst-free techniques as demonstrated by the group of (Ortiz-Martínez et al., 2016; Salar-García et al., 2016); with a maximum biodiesel yield of 99.6% obtained for biodiesel production from *Jatropha* oil. Despite all these advancements, the determining factor in choosing the catalysts to be used in biodiesel production still hinges on the economic viability of the resulting biodiesel fuel. Hence, the reason behind the current popularity of NaOH and KOH is relatively cheap price. It is believed that the production of biodiesel should not rely on one source of feedstocks and the use of a single catalyst only. By taking lessons from the past on dependency on fossil fuels, the overreliance on a single feedstock or material will result in the fundamental economic problem of resource scarcity, especially in the long term. As such, the research communities continue to explore new possible source of feedstocks and catalysts for biodiesel production; more varieties of feedstocks that are available and tested will lead to more assurance towards biodiesel in terms of sustainability and feasibility.

2.2. Biodiesel feedstock

Biodiesel is mono-alkyl esters derived from long chain fatty acids that can be made from renewable lipid feedstock such as animal fats and vegetable oils that are available in large amount in nature. Biodiesel is considered as one of the candidates to replace petroleum-based fuels because its characteristics are almost similar to diesel, but it produces less emissions, free of sulfur, biodegradable and has a higher cetane number (Silitonga et al., 2013b). There are many types of feedstock that can be used as biodiesel. The first-generation feedstocks of edible vegetable oil attracted the attention of recent researchers, but these first-generation feedstocks pose issues such as food versus fuel issue and environmental problems as well as fear of starvation in developing countries. Therefore, the second generation of feedstocks derived from non-edible vegetable oil has gained interest to become a feedstock for biodiesel production. In addition, the second-generation feedstock has been proven to be very promising for biodiesel production in a sustainable manner, both from its availability and physical properties (Sharma, 2010; Silitonga et al., 2016a; Silitonga et al., 2016b). Table 2.1 shows there are some potential feedstocks in countries around the world for the production of biodiesel. On the feasibility of biodiesel production in the future, it is very important to do a thorough evaluation of the physical and chemical features of raw material crude edible and non-edible. Various properties of the chemical and physical properties of raw materials, edible and non-edible can be seen in this literature (Atabani et al., 2012; Mofijur et al., 2013b; Silitonga et al., 2013a; Singh, 2010).

Table 2.1: Current potential feedstocks for biodiesel production worldwide (Atabani et al., 2012; Mofijur et al., 2013b; Silitonga et al., 2013a; Singh, 2010).

Country	Feedstocks
Argentina	Soybeans
Brazil	Soybeans/palm oil/castor/cotton oil
Canada	Rapeseed/animal fat/soybeans/yellow grease and tallow/mustard/flax
China	Waste cooking oil/rapeseed
France	Rapeseed/sunflower
Germany	Rapeseed
Greece	Cottonseed
India	*Jatropha curcas L*/*Pongamia pinnata* (karanja)/soybean/ rapeseed/sunflower/peanut
Indonesia	Palm oil/jatropha/coconut/*Ceiba pentandra*/ *Sterculia foetida L*/ *Calophyllum inophyllum L*
Ireland	frying oil/animal fats
Italy	Rapeseed/sunflower
Japan	Waste cooking oil
Malaysia	Palm oil
Mexico	Animal fat/waste oil
New Zealand	Waste cooking oil/tallow
Philippines	Coconut/jatropha
Spain	Linseed oil/sunflower
Sweden	Rapeseed
Thailand	Palm/jatropha/coconut
UK	Rapeseed/waste cooking oil
USA	Soybeans/waste oil/peanut

2.2.1. The edible vegetable oils

2.2.1.1. Peanut

Oil-based biodiesel from peanut (*Arachis hypogea L*) is produced in the United States, India, China and some other areas of the country (Moser, 2012). A peanut is a plant that

grows in many parts of the Mediterranean region and the bean is an annual plant (Aydin, 2007). The first research group that considered peanut oil as a fuel suitable for diesel engines are (Fasina, 2008; Pérez et al., 2010). However, the traditional peanut oil prices are so high and unstable, making it uneconomical for biodiesel production on a large scale (Davis et al., 2009; Pérez et al., 2010). The study found that it functions very well comparable to cooking oil that consists of 45-50% of oil content (Davis, Dean, Faircloth, & Sanders, 2008). The percentage of oleic acid in traditional peanut oil reaches 40-67%, whereas high cultivate can reach up to 80% oleic (Davis et al., 2008; Pérez et al., 2010). A distinct advantage of using biodiesel derived from peanut oil is its capability of improving the cold flow properties (Pérez et al., 2010). Additionally, Tosun, et al., (Tosun et al., 2014) stated that adding an amount of 20% alcohol (by vol.) with the methyl ester of peanut oil can help improve the performance of the engine. Ertaç Hürdoğan (2016) has conducted an analysis of diesel engines using diesel fuel and biodiesel derived from peanut. It is concluded that the performance of the engine with diesel fuel and biodiesel from peanut oil showed almost similar results in engine performance in terms of energy efficiency and energy efficiency. From the experiment results, the efficiency of engine reached 34% and 35% for biodiesel and diesel fuel, respectively. Besides that, the energy efficiency of biodiesel fuel from peanut is determined as 33% and diesel fuel as 32% (Hürdoğan, 2016). Furthermore, Hanbey Hazar et al. (2016) have investigated the use of peanut oil as biodiesel fuel in low heat rejection diesel engines. In the study, biodiesel from peanut oil was produced through transesterification method. The test on the engine is done by using diesel, biodiesel and mixture of both fuels. The results showed that the use of biodiesel as a fuel in a diesel engine will decrease fuel consumption, hydrocarbon, smoke density value and carbon monoxide. Followed by exhaust gas temperature, thermal efficiency, and carbon dioxide increased (Hazar et al., 2016).

2.2.1.2. Canola (rapeseed)

Canola is one of the raw materials that produces a lot of crude oil per unit of land area (Li et al., 2009). Canola oil contains about 40% oil and can produce up to 992 kg per hectare. Due to this reason, canola oil has a very high potential to be planted as oilseed feedstock for biodiesel production. Especially in Canada, canola is one of favorite feedstocks after soybean and sunflower (Dizge & Keskinler, 2008; Smith et al., 2007). The transesterification process is performed to produce canola methyl ester and it is found that it has physicochemical properties comparable to conventional diesel oil (Lang et al., 2001). Canola methyl ester biodiesel is in accordance with European standards because physicochemical properties of canola methyl ester have a long oxidation stability properties and good cold flow properties (Malça et al., 2014). Erkan Öztürk (2015) has conducted research on the characteristics of a diesel engine by using biodiesel fuel from diesel fuel mixed with canola oil. The experiment was conducted using direct injection diesel engine using 5% (B5) and 10% (B10) of biodiesel fuel. The experiment found that along with the addition of the amount from canola biodiesel to diesel caused the delay of injection, maximum heat release and ignition decrease. While at the same time the injection and combustion duration increased. 5% biodiesel fuel blends (B5) showed an increase in combustion resulting in lower CO_2 and smoke emissions, while also increased NO_x emissions. In contrast, the combustion process using 10% (B10) biodiesel fuel mixture has decreased due to high surface tension, viscosity and density. Therefore, the emission NOx value decreases as CO and smoke emission value increases. The CO_2 emission values in both mixtures are almost equal (Öztürk, 2015).

2.2.1.3. Soybean

Soybean oil is a raw material used for biodiesel production in Brazil. Up to 80% of the use of biodiesel in Brazil derived from soybean oil (Corseuil et al., 2011). Soybean oil

contains free fatty acids (FFA) 3-50 wt. %), Sterols (7-8%), tocopherols (3-12%), triglycerides (45-55%), unsaponifiables and other hydrocarbons (Yin et al., 2015). Triglycerides consist of oleic, linoleic, stearic and palmitic linolat (Balat & Balat, 2010). In soybean oils, the essential fatty acids which are unsaturated undergo oxidation to form the compounds of free fatty acid oil. But biodiesel derived from soybean oil is particularly vulnerable to its oxidative nature if stored for a long period of time, typically a month (de Sousa et al., 2014). The solution to inhibit oxidation can be done by providing some kind of antioxidants in the biodiesel from soybean oil to reduce the propagation and the initiation of free radicals (Kreivaitis et al., 2013). Özer Can et al. (2016) has undertaken research using biodiesel fuel from soybean oil in single cylinder, direct injection (DI), four-stroke diesel engines through a combination of biodiesel additions and EGR (exhaust gas recirculation) applications with different levels (5, 10, 15 %) of exhaust emissions and combustion. In their research, biodiesel from soybean oil was mixed by 20 % vol. with diesel fuel. From the experimental results it was found that the maximum pressure in the cylinder and maximum heat release generally increased due to the combined effect of biodiesel addition and EGR application. In addition, high engine loads cause NOx emissions and smoke to increase synchronously up to 55% and 15% (Can et al., 2016).

2.2.2. The non-edible vegetable oil

2.2.2.1. Calophyllum Inophyllum

Calophyllum inophyllum (kamani) is a tree that grows in East Africa, through South East Asia to India, Taiwan, the Philippines and the Marianas. This tree comes from the family of Clusiaceae. The tree is light and able to withstand nature xerophytic habitat where these trees can flourish. Immature or mature tree size ranges from 8-20 m (25-70 ft). The land which the trees grow required around 750-5000 mm rainfall. The tree can bear fruit twice a year. In one-hectare area, the plantation can sustain up to 400 trees.

The fruit of this tree is initially pink-green before turning into green light when matured, eventually turn back dark grey-brown and wrinkled. For every 1 kg of *Calophyllum inophyllum*, there can be around 150-200 seeds. 100 kg (220 lb.) beans in the extraction could produce 5 kg (11 lb.) of crude oil. The oil content of the seeds of *Calophyllum inophyllum* is up to 65%. *Calophyllum inophyllum* is a potential source of alternative fuels due to the fact that it is easily cultivated. There have been many studies showing that alternative fuels such as biodiesel can be obtained and prepared from the plant through several stages. The fuel produced is suitable for usage in diesel engine. Crude oil *Calophyllum inophyllum* has an acidic value of 59.30 mg KOH/g and FFA content of 29.38%. The fatty acid compositions of *Calophyllum inophyllum* crude oil are (1). are (1). C16: 0 = 14.8-18.5%, (2).C18: 0 = 9.2-15.9%, (3). C18: 1 = 36.2-53.1, (4). C18: 2 = 15.8 -28.5% and (5). C22: 1 = 3.3% ((WAC), 2009; Ong et al., 2011b). Vairamuthu et al. (2016) has investigated biodiesel from *Calophyllum inophyllum* oil in direct injection (DI) diesel engines against emission, engine performance and combustion process. In this study, the diesel fuel was mixed with biodiesel from *Calophyllum inophyllum* oil with varied volume proportions (25%, 50% and 75%). From the experimental results, the B25 showed better engine performance than the pure diesel by 27% improvement. Besides, the performance of the engine for biodiesel B50 obtained equal to that of diesel fuel. The characteristics of the smoke density for B25 fuel showed slightly higher than diesel fuel by 2.6% under maximum load conditions. From the experimental results, it was observed that the biodiesel mixture with diesel fuel did not show any knocking problem and the combustion process was smoother than diesel fuel (Vairamuthu et al., 2016). Another study that has been done by Nanthagopal et al. (2016) using *Calophyllum inophyllum* as biodiesel indirect injection diesel engines to investigate the effect of injection pressure. The injection pressure was set to 200, 220 and 240 bars using 100% biodiesel as experimental results comparison with pure diesel,

which showed that the use of *Calophyllum inophyllum* biodiesel can save fuel consumption at higher injection pressure. Besides, the carbon monoxide, smoke opacity and hydrocarbon emissions were observed to decrease significantly compared to other fuels. However, the oxide of nitrogen from *Calophyllum inophyllum* biodiesel fuel is always higher than neat diesel along with the increased pressure of injection (Nanthagopal et al., 2016).

2.2.2.2. Ceiba pentandra

Ceiba pentandra L. Gaertn. belongs to the family of *Bombaceae* and locally known as kapok or kekabu plants, grown in the states of Southeast Asia, Indonesia, Sri Lanka, Malaysia and other parts of the tropical country East Africa. Each fruit seed contains oil about 25-28% (w/w) of the weight and reportedly resembles edible cottonseed oil. Extraction of crude oil from cotton seeds as average about 1280 kg/ha. In the traditional way, kekabu fibers can be used as stuffing material for pillows (Yu et al., 2011). The brownish-black seeds embedded in *Ceiba pentandra* produces fiber mass. Therefore, the kapok tree can be used as raw materials for biodiesel production and for manufacturing of soap. Other uses of the tree include the production of wool while the residue can also be used for animal feed or as fertilizer (BPI, 2012; Jøker & Salazar, 2000; Ong et al., 2014b; Salimon & Kadir, 2005; Silitonga et al., 2013e). In this study, it was found that cotton from this tree has the potential to produce cellulosic ethanol for cotton fiber containing 34-64% of cellulose. In addition, the crude oil contains pairs of unique cyclopropenoid fatty acid (acid malvalic) with unsaturated carbon bond that is more reactive with atmospheric oxygen. Therefore, the hydrocarbon chain reduces the stability of rapid oxidation of palmitic acid (Bindhu et al., 2012). Palanivelrajan and Anbarasu (2016) have investigated the performance and emissions of biodiesel fuels from *Ceiba pentandra* in diesel engines. The tested fuel was mixed with diesel fuel at the varied blend ratio of B10 (10%), B20 (20%), B30 (30%), B40 (40%) and B50

(50%). From the experiments, the mixture B10 showed the best results in term of physicochemical properties and performance of diesel fuel among other mixtures. Along with the increase in the percentages of biodiesel-diesel blends, the thermal brake efficiency decreases. However, the B10 mixture showed similar characteristics with diesel fuel in terms of emissions and engine performance. In conclusion, B10 *Ceiba pentandra* biodiesel-diesel fuel is one of the most effective fuels for diesel engines (Palanivelrajan & Anbarasu, 2016).

2.2.2.3. Jatropha curcas

Jatropha curcas (*J. curcas*) is a plant that originated from the Central America (Mexico) under the family of *Euphorbiaceae* plants. The plant has 170 species of the genus that are spread throughout the world with the height measuring 5-7 m (Huerga et al., 2014; Silitonga et al., 2013e). *Jatropha curcas* has been found to be one of the best raw material to produce biodiesel. The raw materials are non-edible and cannot be eaten. So, it will not compete with food crops that making it relatively cheap. *Jatropha curcas* contains high acid index (Luu et al., 2014). This plant can produce up to 1,590 kg of crude oil / hectare and has the potential to be crude oil feedstock for the production of biodiesel (Atabani et al., 2013a; Huerga et al., 2014; Silitonga et al., 2011). *Jatropha curcas* fatty acid methyl ester (FAME) can be produced up to 97% and the plant has an oil content ranging from 30-40% (Rabiah Nizah et al., 2014). The Jatropha contains oleic acid 44.5%, 35.4% linoeic acid, palmitic acid and 13%, and thus the plant is feasible to produce a biodiesel (Silitonga et al., 2013d). Crude oil from seeds derived from the plant *Jatropha curcas* can be produced using mechanical extraction and chemical extraction methods. Mechanical extraction methods use a screw press or the press ram driven by an engine and can produce 60-65% wt. of crude oil while chemical extraction methods use solvents such as n-hexane commonly generate 75-80% wt., but the method of using chemicals is not recommended due to its impact to the

environment (Chen et al., 2012). Fernández et al. (2015) conducted experiment using *Jatropha curcas L*. oil for biodiesel production through supercritical extraction and fractionation. This study evaluated the effect of condition process on oil yield, oil quality and free fatty acid content from *Jatropha curcas* oil. From the results of experiments, the free fatty acid (FFA) obtained was as high as 26 wt. %. Removal results in 91 wt. % along with increase of pressure on testing with low fatty acid content of 1 wt.% (Fernández et al., 2015). The optimization through the response surface method in extracting oil from *Jatropha curcas* has been done by Subroto et al. (2015). The experiment was carried out using laboratory scale hydraulic equipment, with applied pressure ranges from 10-20 MPa at 60-90 °C pressing temperature, and the water content ranging from 3-5%. From the experiments, about 87% of oil yield was obtained under the optimum extraction conditions at 19MPa pressure with 90 °C pressing temperature and 3.8% water content (Subroto et al., 2015).

2.2.2.4. Sterculia foetida

Sterculia foetida is a plant that has been planted in many parts of the world such as Malaysia, Indonesia, Philippines, Myanmar, Australia, Pakistan, Sri Lanka, Thailand, Bangladesh, Oman and India ((WAC), 2010). This plant comes from the family of *Sterculiaceae* which contains approximately 2,000 different species throughout the world and is classified as non-drying oil. These plants can live in the tropics and sub-tropics, besides that this plant is a wild plant that can live up to 100 years. *Sterculia foetida* tree has a diameter ranging from 100-120 cm tall and can grow up to 40 meters, so it is ideal for planting at the plantation land of roughly 3x3 m. This plant can produce 250-350 kg of grain per year and has a large fruit size range from 10cm in length, red and smooth, with about 10-15 black seeds in each fruit when ripe (Silitonga et al., 2013c). Crude *Sterculia foetida* oil contains protein of 21.61% and fat 51.78%. In addition, *S. foetida* is composed of sterculoyl acid 35.1%, 25% saturated fatty acids,

15.3% of unsaturated fatty acids and 1.7% malvaloyl acid, so the crude oil *Sterculia foetida* is suitable for production as biodiesel in the future. A recent study has been done by Sethusundaram et al. (2016) on using biodiesel from *Sterculia foetida* in a single cylinder four stroke diesel engine. Crude *Sterculia foetida* oil was processed through transesterification method using 2 wt. % of KOH catalyst and 20% methanol. Biodiesel *Sterculia foetida* was mixed with diesel fuel at 25% (B25), 50% (B50), 75% (B75) and 100% (B100) (Sethusundaram et al.).

2.2.2.5. Karanja

Karanja (*Pongamia pinnata*) is one of the most widely raw materials available in addition to *Jatropha curcas* for biodiesel production (Agarwal & Dhar, 2009, 2013; Dhar & Agarwal, 2013, 2015a). *Karanja* trees are generally used as tree ornaments. *Karanja* trees grow and spread in the sub-continent of India and some parts of Southeast Asia. *Karanja* belongs to the *Leguminaceae* family. This tree is very flexible because it can be planted in the land and does not require any treatment. This tree is a middle size tree with a trunk diameter above 50 cm and the height of the tree can go up to 18 m. Crude oil from the *Karanja* seed extract is generally bright yellowish orange color and quickly turn into dark black after long storage. The composition of fatty acids from crude Karanja oil is palmitic acid, stearic acid, oleic acid, linoleic acid, eicosanoic acid, docosanoic acid and tetracosanoic acid, which are 11.65%, 7.50%, 51.59%, 16.64%, 1.35%, 4.45% and 1.09%, respectively. *Karanja* oil generally can be a raw material of soap and also often used for traditional ointment oil for rheumatic diseases. Besides, the leaves can be juiced and used as cough medicine, diarrhea, colds, stomach pain, and others (Baiju et al., 2009). *Karanja* trees can produce seeds by approximately 4-9 tonnes/ha. The Karanja seed contains 25-40% w crude oils. *Karanja* has become one of the potential sources of raw materials to produce biodiesel (Agarwal et al., 2015; Takase et al., 2015). *Karanja* crude oil contains high amounts of free fatty acids with

high FFA which means it requires pretreatment before performing esterification and transesterification. That is aimed to reduce fatty acid to below 1 % to produce biodiesel conforming ASTM and EN standards via the transesterification process using alkali catalyst (Kamath et al., 2011; Sharma & Singh, 2011). High percentages of FFA in the crude *Karanja* oil can lead to the formation of soap with a base-catalyst and disrupt the process of transesterification. However, two-step method has been obtained by the transesterification process using an acid-catalyst and base-catalyst proved successfully to produce quality biodiesel and in accordance with the standard (Dhar & Agarwal, 2015b).

2.2.2.6. Reutealis trisperma

Reutealis trisperma or locally known as Philippine Tung is one of the non-edible oils, belongs to the family *Euphorbiaceae*, and is a native plant in the Philippines and Southeast Asia. This plant is a timber species and the wood usually used for carving and furniture. Meanwhile the seeds are commonly used as traditional medicine and its bark sap is used as a scabies medicine ((ISC), 2016; Aunillah & Pranowo, 2012; Pranowo, 2014). The plant can grow up to 10-15 m (33-50 ft) in favorable conditions, e.g. within low (700 mm) to high (2500 mm) rainfall climate. The tree can produce 25-30 kg of dry beans per tree per year. The *Reutealis trisperma* seed contains 50-52% (w/w) of crude oil. The width and length of the leaf blade of the *Reutealis trisperma* plant are around 12-14 cm and 12-13 cm, respectively. The leaf shaped ovate or ovate-cordate. The trunk and petiole are about 35 cm and 14-15 cm, respectively ((FOC), 2016; Holilah et al., 2015; Kumar et al., 2015; Wirawan, 2007). Crude *Reutealis trisperma* oil contains about 19.5 % saturated fatty acids and 35.3% of unsaturated fatty acids. The fatty acid composition of crude *Reutealis trisperma* oil are palmitic acid, oleic acid and linoleic acid, which are 13.1 %, 16.1 % and 18.7 %, respectively. The plants of *Reutealis trisperma* can be found around the countryside of Malaysia, Indonesia, China, India,

Cuba, and the Dominican Republic. In Indonesia, *Reutealis trisperma* is especially distributed in West Java. Recently, it is being cultivated in the Sumedang area, West Java, Indonesia. Figure 2.1 shows the distribution map of the *Reutealis trisperma* plant around the world (Corporation, 2016; IUCN, 2014; Nurjanah et al., 2015; U.S., 1966; Wahyudi et al., 2009). The analysis of suitability and land required for *Reutealis trisperma* plant in West Java Province was investigated by Wulandari et al. (2014). This analysis was based on the Geographic Information System (GIS) data. The determination of numerical weights was done through Analytical Hierarchy Process (AHP) method using land criteria and climate criteria accordance with Indonesian territory. From the analysis, there are 981.067 Ha of land suitable for *Reutealis trisperma* plant spread over 23 regencies in West Java Province. From the analysis results, *Reutealis trisperma* is highly recommended to be planted as an alternative energy supply and environmental rehabilitation in Indonesia (Wulandari et al., 2014). Furthermore, the protein content in the remaining biomass from oil extraction from *Reutealis trisperma* seed is relatively high. The protein content is about 62% of the cake that exists after the oil extraction process from the ripe endosperm. In addition, *Reutealis trisperma* fruit that is overripe contain higher protein in endocarp and cake as much as 73%. From these results, it can be seen a great potential from the residue of the biomass extracted from seed oil *Reutealis trisperma* to be an animal feed product.

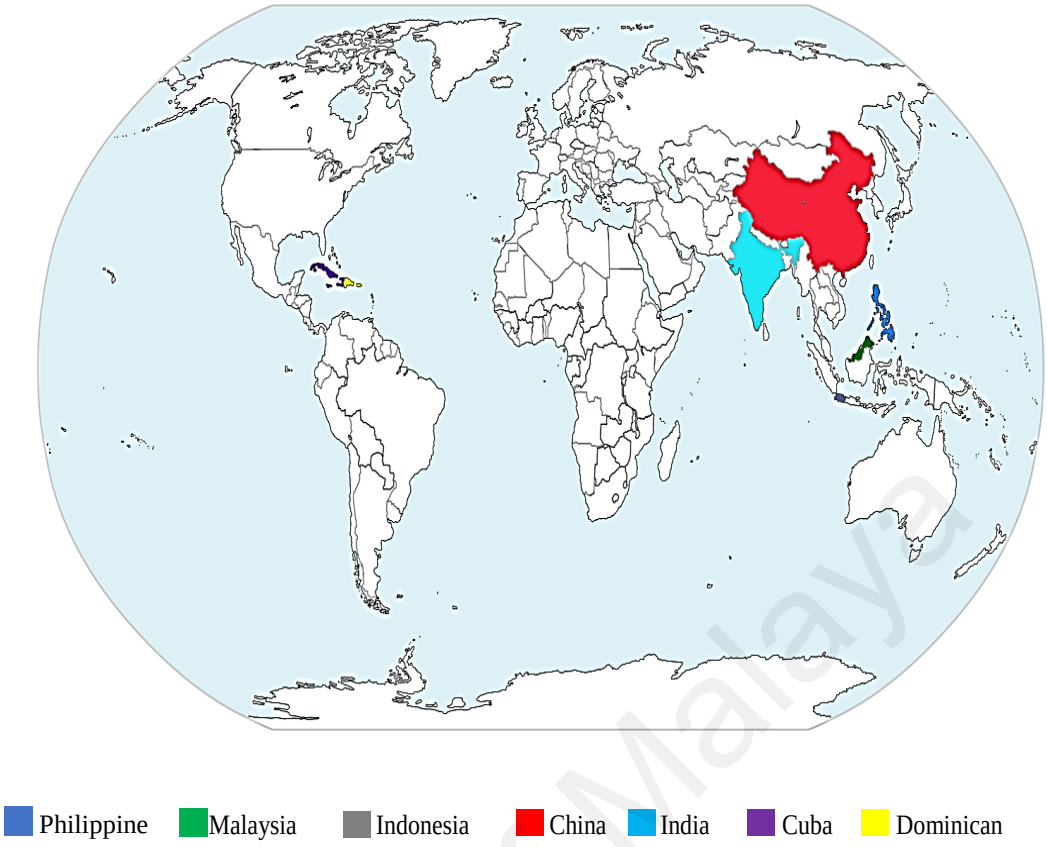


Figure 2.1: Distribution map of *Reutealis trisperma* plant around the world (Corporation, 2016; IUCN, 2014; Nurjanah et al., 2015; U.S., 1966; Wahyudi et al., 2009)

2.3. Biodiesel production

Researchers have done various innovations in developing biodiesel production from various feedstocks available. The production from palm oil through conventional and ultrasonic processes using alkaline earth metal oxide catalysts (CaO, SrO and BaO) delivered by Mootabadi et al. (2010). In the process of experiment, it was stated that 60 minutes is the optimum conditions for achieving a yield of up to 95% compared to 2-4 hours for a conventional magnetic stirring method. In addition, from three types of catalyst used under optimum conditions, the yield increased from (CaO) 5.5% to 77.3%, (SrO) 48.2% to 95.2%, and (BaO) 67.3% for 95,2% through ultrasonication process (Mootabadi et al., 2010). In addition, Ali et al. (2013) investigated the characteristics of the biodiesel production from palm oil via alkali catalyst transesterification. The results

showed that the optimum reaction of a palm oil methyl ester is at temperature of 60 °C and the reaction time is 60 minutes and achieved 88% yield of biodiesel (Ali & Tay, 2013). Apart from that, Choedkiatsakul et al. (2014) studied the production of biodiesel combining conventional mechanical stirring and ultrasonic. From the results of ultrasonic process, it was indicated the optimal conditions with the molar ratio of oil is 6 and 1% wt. NaOH catalyst of oil to produce the highest palm oil methyl ester up to 94% obtained within 5 minutes of reaction time. Transducer was placed at 4 locations along the reactor with a frequency of 20 and 50 kHz, whereas conventional mechanical stirring is required for 60 minutes of reaction time at speed 160 rpm (Choedkiatsakul et al., 2014). Therefore, it is evident that in the biodiesel ultrasonic method was very effective and useful to shorten the reaction time during esterification and transesterification process

Biodiesel production from crude oil *Calophyllum inophyllum* which contains high free fatty acid (19:58%) was studied by Chavan et al. (2013). *Calophyllum inophyllum* methyl ester is produced through a two-stage process of esterification and transesterification. The first stage is an esterification process via an acid catalyst to reduce the levels of free fatty acids to below 1% and the second process is transesterification process to achieving yield of 83% (Chavan et al., 2013). Ong et al. (2014) also conducted research on crude oil *Calophyllum inophyllum* by optimizing the production of biodiesel through a two-stage process; acid catalyzed esterification and alkali catalyzed transesterification. The final result of *Calophyllum inophyllum* methyl ester showed the yield, 98.92% was obtained at a temperature 50 °C with methanol to oil ratio of 9:1 using 1 % NaOH catalyst for 1 hour (Ong et al., 2014a).

Ayodele and Dawodu (2014) presented the production of biodiesel from *Calophyllum inophyllum* oil. High conversion of *Calophyllum inophyllum* methyl ester up to 99% by

using a cellulose-derived catalyst (solid acid catalysts derived from sulfonated aromatic carbon derived from the pyrolysis of microcrystalline cellulose) was achieved. Results were achieved at a temperature 180°C with a catalyst loading of 5% and methanol to the oil molar ratio 1:15 M for 4 hours (Ayodele & Dawodu, 2014). Furthermore, Silitonga et al. (2013) studied the potential and the characteristics of crude *Ceiba pentandra* oil for biodiesel production and the effects of diesel blend to biodiesel properties in order to improve biodiesel quality. The biodiesel was produced through two-stage esterification-transesterification of acid-base catalyst (H_2SO_4 and NaOH) and the results showed that the properties of *Ceiba pentandra* methyl ester conform to the ASTM D6751 and EN 14214 standard. Besides, biodiesel blend with diesel fuel is recommended to improve the quality of biodiesel properties such as density, calorific value and viscosity (Silitonga et al., 2013b). Moreover, Ong et al. (2013) investigated the optimization of the biodiesel production from crude *Ceiba pentandra* oil via supercritical methanol transesterification without catalyst. From the experimental results, the optimum conditions to produce fatty acid methyl ester up to 95.5% are temperature 322 °C for reaction, the molar ratio of oil 30:1 with a pressure of 16.7 MPa and reaction time of 476 s (Ong et al., 2013b).

Sivakumar et al. (2013) studied the optimization on crude oil *Ceiba pentandra* underutilization in India. The biodiesel production process from *Ceiba pentandra* oil was done through two stages of esterification and transesterification via acid-base catalyst. The optimization results demonstrated that the optimum conditions are methanol oil molar 6:1 and 1.0 wt.% KOH at a temperature of 65 °C for 45 minutes. The observed FAME yield up to 99.5% that was successfully converted under those optimum conditions (Sivakumar et al., 2013). Apart from that, the study of biodiesel production on three non-edible crude oil that are *Jatropha curcas*, Sterculia *foetida* and *Ceiba pentandra* has been studied by Ong et al. (2013). The biodiesel production

processed through acid-esterification (H_2SO_4) and alkali-transesterification (NaOH). The yield results were obtained at the optimum condition for three different feedstocks of biodiesel and they were 96.75%, 97.50% and 97.72%, respectively. Besides that, the properties of three biodiesel have been observed and matched with biodiesel standard ASTM 6751 and EN 14214 (Ong et al., 2013a).

Taufiq-Yap et al. (2014) also studied the production of biodiesel from crude *Jatropha curcas* oil through the transesterification process using a solid heterogeneous mixed oxide (CaO-La2O3) as a catalyst. The research was carried out in optimum conditions with a 4% catalyst and oil molar ratio of 24:1 at temperature 65 °C, the final product fatty acid methyl ester yield was 86.51% (Taufiq-Yap et al., 2014). On the other hand, Dharma et al. (2016) investigated the optimization of biodiesel production process from mixed crude *Jatropha curcas-Ceiba pentandra* oil using response surface methodology. The result showed that the mixed percentage of crude *Jatropha curcas-Ceiba pentandra* oil was 50%:50%. The transesterification process was carried out at the optimized condition based on the parameters of response surface methodology, with oil ratios (methanol: 30%), temperature 60 °C, the catalyst potassium hydroxide (KOH) of 0.5% for 2 hours with stirring speed of 1300 rpm which led to the highest yield of 93.33%, Based on the test results exhibited, the physicochemical properties of biodiesel from *Jatropha curcas crude-Ceiba pentandra* mixed oil increased the quality level of biodiesel (Dharma et al., 2016).

The optimization of biodiesel production from crude *Sterculia foetida* oil, which has a high fatty acid and viscosity have been investigated by Silitonga et al. (2013). The experimental process used design of experiment for optimization parameter such as the speed of stirring, catalyst, reaction time and temperature. Parameter optimization of biodiesel production was carried out in two steps of esterification and

transesterification. The parameters for the esterification is determined to the best at a speed of 1200 rpm stirring, 1% sulfuric acid catalyst, methanol to oil ratio of 12:1 and temperature at 60 °C for 3 hours. For transesterification process the catalyst used was sodium hydroxide (NaOH) in the amount 1%, at a temperature of 55 C, methanol 12:1, for 2.5 hours reaction time to produce a maximum methyl ester conversion of 93.55%. The results of *Sterculia foetida* methyl ester have been tested in accordance with ASTM D 6751 and EN 14214 standards (Silitonga et al., 2013c). However, other relevant studies also showed that the production of biodiesel from *Sterculia foetida* using cellulose sulfonic acid catalyst by (Anusorn Vorasingha 2017). In the experiments, the process showed that by using cellulose sulfonic acid as a catalyst, the material can be converted into biodiesel at one stage of the process until it reaches 98.5% yield with a combination of methanol to oil ratio of 9:1 at a temperature of 80 C and 5% catalyst cellulose sulfonic acid (Vorasingha, 2017).

Thiruvengadaravi et al. (2012) analyzed the crude oil Karanja (*Pongamia pinnata*) to be converted into fatty acid methyl ester through a two-stage esterification and transesterification process. That two-stage process is carried out to reduce free fatty acids and to reduce the acid value to 1.3 mg KOH/g from 12:27 mg KOH/g. For the 2-hour esterification process, the optimum parameter combination that has been used is of the ratio of methanol to oil 9:1 and 1% sulfated Zirconia (SZ) as solid acid catalyst at temperature 60º C. This is followed by alkali catalyzed transesterification process with 1% KOH and methanol to oil molar ratio of 6:1 for 2 hours. The production of biodiesel achieved yield up to 95% and the physicochemical properties of Karanja biodiesel has been tested following the ASTM D6751 standard (Thiruvengadaravi et al., 2012). Another research on biodiesel production has been done by Holilah et al. (2015) using crude *Reutealis trisperma* oil. The production of biodiesel through esterification and transesterification process was achieved with yields of up to 95.15% under optimum

conditions. The parameters used in the transesterification process are 1% NaOH as a catalyst, temperature of 65ºC with methanol to oil molar ratio of 1:1, at a constant stirrer speed for 1 hour. From the results shown the physical properties following the ASTM D6751 standard, only two properties exceed the minimum limit such as conradson carbon residue (CCR) and viscosity (Holilah et al., 2015; Wahyudi et al., 2009).

Furthermore, the other previous study on biodiesel production has been done by Djenar et al. (2012) on esterification of crude *Reutealis trisperma* oil in biodiesel production. The experiment was conducted through esterification and transesterification process. The esterification process was carried out for 60 minutes at 60°C, oil-to-methanol ratio 4:1, 1.5% sulfuric acid (H_2SO_4) while the transesterification process was performed for 30 minutes at 50 °C, 1 wt.% KOH catalyst. The result was found 99.5% methyl ester with the largest chemical composition content were 29.97%, 38.03%, and 27.55% for methyl palmitate, methyl oleate, and methyl linoleate, respectively. In addition, Aunillah et al. (2012) has conducted an experiment on biodiesel production from *Reutealis trisperma* using the two-stage transesterification method. 50 liters of crude *Reutealis trisperma* oil is used for biodiesel production, 11.5-liter methanol, 96 g catalyst KOH. The transesterification process is carried out at 60°C for 45 minutes reaction time, and then the second stage of transesterification is carried out for 30 minutes at 60 °C with addition of 20% methoxide solution. The biodiesel is washed for 15 minutes with warm water to remove residual impurities in the biodiesel. The result has found that 44 liter (88%) yield of biodiesel and has characteristic properties such as acid value 0.105 mg KOH/g, kinematic viscosity at 40 °C is 4.4 mm^2/s, density 881.2 kg/m^3, calorific value 39.78 MJ/kg and flash point 129.5 °C (Aunillah & Pranowo, 2012).

Djeni Hendra (2014) studied the biodiesel production from seed of *Reutealis trisperma*. The biodiesel production is performed through the esterification process for 1 hour at temperature 60°C, 20% methanol and 1% (v/v) acid catalyst (H_2SO_4). The transesterification process is carried out for 1-hour at temperature 60°C, 10% (v/v) methanol and 0.6 wt. % NaOH catalyst. The result found that 79.92% yield of biodiesel and the physicochemical properties of biodiesel oil to have a density of 865 kg/m^3, kinematic viscosity 5.41 mm^2/s at 40°C and acid value of 0.76 mg KOH/g (Hendra, 2014). Nurjanah et al. (2015) has analyzed the effect of NaOH catalyst concentration and length of reaction time on the esterification and transesterification of the FAME characteristics of *Reutealis trisperma*. The experiments are performed randomly with two repetitions using a catalyst variation of NaOH (0.75%, 1%, and 1.25%) and reaction time for esterification-transesterification are 1 hour and 2 hours, respectively at 60°C and stirrer speed: 350 rpm. The highest yield of FAME was 61.1% with physicochemical properties; acid value: 0.552 mg KOH/g, kinematic viscosity at 40 °C 5.325 cSt, iodine value 46.6972 g I_2/g and density 0.8703 g/cm^3 (Nurjanah et al., 2015).

The Table 2.2 shows a number of previous studies that have been conducted with different production methods and different feedstocks as well as variations in operating conditions. There are many differences among those different methods based on reaction time and yield. As shown in Table 2.2, the ultrasonic method takes shorter reaction times to produce higher yields than conventional methods and consumes less energy during shorter reaction times. Based on the table, there are several researchers who have investigated the production of *Reutealis trisperma* using conventional methods. However, there are very limited information in literature on the production of biodiesel from *Reutealis trisperma* using ultrasonic methods. Therefore, the purpose of this study was to investigate how effective would the use of ultrasonic methods be on

biodiesel production from crude *Reutealis trisperma* oil as compared to conventional methods.

Table 2.2: Comparison of ultrasonic and conventional method for biodiesel production

Production method	Feedstock	Operating conditions	Yield	Reference
Ultrasonic	Triolein	40 kHz, 25°C < 20 minutes	98%	(Hanh et al., 2008)
Ultrasonic	Sunflower	24 kHz, 60°C, 20 minutes	97%	(Georgogianni et al., 2008)
Conventional	Sunflower	600 rpm, 60°C, > 4 hours	88%	(Georgogianni et al., 2008)
Ultrasonic	Fish oil	20 kHz, 60°C, 1 hour	98%	(E. et al., 2007)
Ultrasonic	Palm oil	20 kHz, 65°C, 1 hour	95%	(Mootabadi et al., 2010)
Conventional	Palm oil	800 rpm, 65°C, 2-4 hours	95%	(Mootabadi et al., 2010)
Conventional	Beef tallow	600 rpm, 60°C, 1 hour	91%	(Teixeira et al., 2009)
Ultrasonic	Beef tallow	20 kHz, 60°C, 70 minutes	92%	(Teixeira et al., 2009)
Ultrasonic	Silybum marianum	40 kHz, 60°C, 20 minutes	95%	(Takase et al., 2014)
Conventional	Silybum marianum	600 rpm, 60°C, 70 minutes	95%	(Takase et al., 2014)
Ultrasonic	Jatropha curcas	Amplitude (~60%), 65°C, 40 minutes	91%	(Deng et al., 2010)
Conventional	Jatropha curcas	1000rpm, 60°C, 3 hours	97%	(Ong et al., 2014b)
Ultrasonic	Fishmeal plant waste oil	20 kHz, 55°C, 30 minutes	87%	(Maghami et al., 2015)
Conventional	Fishmeal plant waste oil	700 rpm, 55°C, 1 hour	79%	(Maghami et al., 2015)
Conventional	Reutealis trisperma	65°C, 3 hours	95%	(Holilah et al., 2015)
Conventional	Reutealis trisperma	350 rpm, 60°C, 3 hours	61%	(Nurjanah et al., 2015)

2.4. Standards properties of biodiesel and diesel fuel

2.4.1. Properties of biodiesel and diesel fuel

The differences of physicochemical properties, chemical composition and content of fatty acids in each raw material affect the outcome of combustion and emissions from the biodiesel fuel (Altun & Lapuerta, 2014; Sorate & Bhale, 2015). Before biodiesel is used directly in diesel engines, there are some important physical properties of biodiesel fuel that should be considered i.e. kinematic viscosity, density, flash point, cloud point, pour point, calorific value and acid value. The physical properties are the main reference standards for biodiesel fuels to be used in diesel engines (Ashraful et al., 2014; Gandure et al., 2014). There are two standards that are commonly used to measure the physical properties of biodiesel fuel, i.e. American standards ASTM D6751 and European Union EN14214 (Ahmad et al., 2014; Dwivedi & Sharma, 2014; Ong et al., 2011a). Some results of physicochemical properties of biodiesel derived from edible oil and non-edible oil feedstocks as well as petrodiesel and ASTM standard D6751 and EN 14214 for biodiesel fuels are shown in Table 2.3 and Table 2.4 (Atabani et al., 2013c; Atabani et al., 2012; Mofijur et al., 2013a) (Al-Widyan & Al-Shyoukh, 2002; Issariyakul et al., 2007; Lertsathapornsuk et al., 2008) (Alptekin et al., 2014; Canakci & Sanli, 2008).

2.4.1.1. Kinematic viscosity

The high viscosity over the standard limit can influence biodiesel fuel performance. It will cause impairment to the flow of fuel to the engine combustion chamber (Ashraful et al., 2014). Besides, high viscosity will cause the formation of engine deposits and soot and can damage the engine in the long run. Kinematic viscosity of biodiesel fuel is determined by the standard ASTM D 6751 (1,9- 6.0 mm^2/s) and EN 14214 (3.5-5.0 mm^2/s) (Sanford et al., 2009). Silitonga et al. (2013) reported that based on an experiment of optimization biodiesel process on *Sterculia foetida*, crude oil has a high

viscosity: 63.90 mm^2/s. The viscosity can be reduced to 3.96 mm^2/s through esterification and transesterification process, the result are in line with the ASTM D 6751 and EN 14214 standard (Silitonga et al., 2013c).

2.4.1.2. Density

Density is the value of measurement of the mass and volume of fluid that is expressed in grams per liter (g/L). The density of biodiesel fuel is a very important parameter because it can have an effect on the efficiency of combustion systems and processes in the fuel injection in diesel engines (Gülüm & Bilgin, 2015; Silitonga et al., 2013a; Verduzco, 2013). The procedure for measuring the density of biodiesel fuels have been determined in accordance with test method ASTM D1298 and EN ISO 3675/12185. The limits of ASTM D6571 and EN 14214 standards are 880 kg/m^3 and 860-900 kg/m^3, respectively. The blends of diesel fuel and biodiesel have been tested by Alptekin and Canakci (2008) to determine the density and viscosity of mixture diesel-biodiesel fuel. There are six variations of volume diesel-biodiesel blends have been tested (B2, B5, B10, B20, B50 and B75). The results found that the density and viscosity value were increased accordance with the increasing ratio of diesel-biodiesel blends (Alptekin & Canakci, 2008).

2.4.1.3. Flash point

The flash point is the range of the temperature at which fuel is going to evaporate and lightened when exposed to sparks. Increment in number of flash point is done to make sure that the storage is safe during transportation of fuels (Boog et al., 2011). Conventional diesel fuel has a flash point ranging from 55-66ºC, while biodiesel typically has a flash point higher than 150ºC. The test method on flash point of biodiesel fuel is measured in accordance with ASTM D93 and EN ISO 3679. Mejía et al. (2013) has performed an analysis on viscosity, cloud point and flash point of the

mixture of diesel fuel in the biodiesel Palm-Castor. The flash point is strongly influenced by the blend ratio of biodiesel-diesel when it is lower than 80%. The flash point of diesel fuel, palm oil biodiesel and castor oil biodiesel are 70ºC, 164ºC and 286ºC, respectively.(Mejía et al., 2013).

2.4.1.4. Cloud point and pour point

Cloud Point is the temperature where oil starts to become saturated as a result of crystallization by cooled settings. Cloud point relates to unsaturated oil. In general, higher unsaturation point results in lower cloud point. Cloud point is measured when a cloud of wax crystals starts to appear when the fuel is cooled to certain conditions during testing. The pour point is the lowest temperature when fuel cannot flow. Generally, the cloud point and pour point for biodiesel are higher than diesel fuel (Demirbas, 2009a). Cloud point and pour point depend on the amount of fatty acids in the raw material used for biodiesel. The ASTM D6751 standards for cloud point and pour point are -3-12ºC and -15-16ºC, respectively. The measurement of cloud point and pour point of biodiesel fuel is performed by using standard test methods: ASTM D2500 and ASTM D97. Research on the cloud point and pour point has been carried out by Dwivedi and Sharma (2015) on *Pongamia* biodiesel oil. In *Pongamia*, biodiesel cold flow properties are the main problem that needed to be improved as the properties of cloud point and pour point are found to be 20ºC and 19ºC, respectively. When *Pongamia* biodiesel mixed with kerosene and diesel fuel, it improves the cloud point from 11.5 to 9ºC and for pours point 12.5 to 11ºC, respectively. Addition of ethanol is found to be the best improvement for cloud point and pour point properties in which the points correlate to 10ºC. In this study, under cold climate the use of *Pongamia* biodiesel-ethanol blends (80:20 %) are recommended (Dwivedi & Sharma, 2015).

2.4.1.5. Calorific value

In the selection of fuels, especially biodiesel fuel, calorific value is one of the most important properties to be considered. Calorific value in ASTM D6751 standard is not specified, but it is determined based on the standard EN 14214 with a standard test method EN 14213. The minimum limit of calorific value for diesel fuel and biodiesel are 42-46 MJ/kg and 35 MJ/kg, respectively. Calorific value of diesel fuel is higher than biodiesel (Balat, 2011; Ramírez-Verduzco et al., 2012). Illman et al. (2000) have investigated the calorific value on *Chlorella* strains by using five types of algal cultures (*Chlorella vulgaris, Chlorella emersonii, Chlorella protothecoides, Chlorella sorokiniana,* and *Chlorella minutissima*) grown in low nitrogen medium. The result shows that biomass of *C. vulgaris* has a low calorific value of 18 kJ/g. The calorific value of *C. vulgaris* when grown in low nitrogen medium has increased to 23 kJ/g. From the five types of algae cultures, *C. emersonii* that was grown in low nitrogen medium contains the highest calorific value, 29 kJ/g. However, the calorific value of 29 kJ/g is lower than the biodiesel fuel limit set by ASTM D6751 and EN 14214 standard (Illman et al., 2000).

2.4.1.6. Acid value

The amount of acid is a parameter of free fatty acids (FFA) contained in the fuel. FFAs are formed naturally from saturated and unsaturated acids derived from mono-carboxylic acids. It is defined as the weight in milligram of KOH required to neutralize the organic acids in 1 gram of fatty acid methyl ester and this measures the FFAs present in the oil (Guo et al., 2013; Ong et al., 2014a). Higher number of FFA will affect acid value. High content of FFA in biodiesel is undesired because it clogs the filter or strainer with sediment which could lead to corrosion of metal in diesel engine (Ong et al., 2014b; Ramadhas et al., 2005). The maximum acid value of biodiesel determined by ASTM D6751 and EN 14214 standards is 0.50 mg KOH/g. Biodiesel

production, process optimization and engine performance tests have been conducted by Ong et al. (2014) using crude *Calophyllum inophyllum* oil that contained high free fatty acid. The acid value contained in crude *Calophyllum inophyllum* oil is 59.30 mg KOH/g. Due to high acid value in crude oil, the biodiesel was processed through several stages such as degumming, esterification, transesterification and neutralization process, so that the acid value can be reduced down to 0.34 mg KOH/g. The physicochemical properties of *Calophyllum inophyllum* biodiesel have been tested and the results showed that *Calophyllum inophyllum* biodiesel is in line with ASTM D6751 and EN 14214 standard (Ong et al., 2014a) .

2.4.1.7. Copper strip corrosion

The copper strip corrosion test is qualitative methods used to determine the rate of corrosion of fuel products using strip parts copper, brass or bronze. In this test, the copper strip is inserted into place where the fuel sample is to be tested, then the copper strips and fuel is heated up to 50ºC in a water bath for three hours, followed by a comparison with a strip ratio of standard to determine the level of corrosion. The test also detects the presence of corrosive hazardous substances, such as acid or sulfur compounds in biodiesel fuel, which can corrode the engine element. The standard test method is specified by ASTM D130 and EN ISO 2160 (Balat, 2011; Masjuki, 2010; Singh & Singh, 2010). Rashid and Anwar (2007) have conducted research on optimization process of biodiesel production from rapeseed oil through base-catalyzed transesterification. The quality of rapeseed biodiesel was evaluated following the ASTM D6751 and EN 14214 standards. One of the properties has been tested is copper strip corrosion following the guidelines of standard test methods specified by ASTM D130 and EN ISO 2160. The results shown that the cooper strip color is golden yellow with the number 1a, which means slight tarnish, the maximum limit for ASTM D6751

and EN 14214 are 3a/3b (dark tarnish) and 1a/1b (slight tarnish), respectively (Rashid & Anwar, 2008).

2.4.1.8. Sulfur content

The sulfur content in diesel fuel and biodiesel from the first distillation (straight-run) is dependent on the origin of the crude oil. In general, the sulfur content in diesel fuel is 50%-60% of the content in crude oil. However, the sulfur content of vegetable oil-based biodiesel fuel is very low (Akbar et al., 2009; Azam et al., 2005). Excessive sulfur content in the fuel will lead to wear and tear on engine parts. This occurs due to the solid particles formed during drying combustion with the presence of sulfur oxides such as SO_2 and SO_3. The characteristics of sulfur content are determined using test method ASTM D5453 and EN ISO 20846/20884. He et al. (2009) investigated the sulfur content in vegetable oils, animal fats and methyl esters of various selected raw materials according to ASTM D5453 test method. The result shows that the sulfur content from various sources of crude oil, animal fats and biodiesel varied. The highest number of sulfur content was found to be 9,000 and 15,000 ppm in rapeseed and mustard oil, respectively. The sulfur content in animal fats and vegetable oils are generally above 15 ppm, but after esterification and transesterification process into biodiesel the sulfur content was significantly reduced to less than 15 ppm. The vegetable oils and animal fats that contained high free fatty acids were recommended to be processed with sulfuric acid before transesterification process to reduce the content of free fatty acids (He et al., 2009).

Table 2.3: Properties of biodiesel from edible feedstocks (Al-Widyan & Al-Shyoukh, 2002; Issariyakul et al., 2007; Lertsathapornsuk et al., 2008)**.**

Properties	ASTM D975 Limit	Petro-diesel	Biodiesel		Test Method		Palm	Peanut	Rapeseed	Soybean	Sunflower	Coconut
			ASTM D6751 Limit	EN 14214 Limit	ASTM	EN						
Kinematic Viscosity at 40 °C (mm^2/s)	2.0-4.5	2.91	1.9-6.0	3.5-5.0	ASTM D445	EN ISO 3104	4.5	4.42	4.44	4.03	4.43	2.72
Density 15 °C (kg/m^3)	850	839	880	860-900	ASTM D1298	EN ISO 3675	864.42	848.5	883	913.8	880	807.3
Acid value (mg KOH/g)	-	0.17	Max. 0.50	Max. 0.50	ASTM D664	EN 14104	0.24	0.28	-	0.26	0.27	0.16
Calorific value (MJ/kg)	42-46	45.83	-	35	-	EN 14214	40.15	40.1	37	39.76	-	-
Flash Point (°C)	60-80	71.5	Min 130	Min 120	ASTM D93	ISO DIS 3679	135	166	170	76	160	114.8
Cold filter plugging point (°C)	-25	-	19	Max.5	ASTM D6371	EN 14214	12	-	-13	11	-3	-4
Pour point (°C)	-15 to 5	1.0	-15-16	-	ASTM D97	-	15	-8	-12	2	-	-
Cloud point (°C)	-35 to 15	2.0	-3-12	-	ASTM D2500	-	16	0	-3	9	3.4	0
Copper strip corrosion (3 hours at 50 °C)	1	1	Max 3	Min 1	ASTM D130	EN ISO 2160	1a	-	-	1b	1a	1b
Sulfur content % (m/m)	0.05	-	Max 0.05	Max 10[a]	ASTM D5354	EN ISO 20846	0.003	0	-	0.8	0.2	3.2
Oxidation stability (hours at 110 °C)	-	23.7 h	Min 3 h	Min 6 h	ASTM D675	EN 14112	10.3 h	2 h	7.6 h	2.1 h	0.9 h	3.55 h
Cetane number	40-55	49.7	Min. 47	Min. 51	ASTM D612	EN ISO 5165	54.6	53.59	54.4	37.9	49	-
Carbon (% wt.)	84-87	88.5	77	-	-	-	-	62.1	81	-	-	-
Hydrogen (% wt.)	12-16	13.5	12	-	-	-	-	-	12	-	-	-
Oxygen (% wt.)	0-0.31	0	11	-	-	-	-	-	7	-	-	-

[a]mg/kg

Table 2.4: Properties of biodiesel from non-edible feedstocks (Atabani et al., 2013c; Atabani et al., 2012; Mofijur et al., 2013a).

Properties	ASTM D975 Limit	Petrodiesel	Biodiesel		Test Method		Calophyllum Inophyllum	Ceiba pentandra	Jatropha curcas	Sterculia foetida	Karanja	Mahua	Cotton seed
			ASTM D6751 Limit	EN 14214 Limit	ASTM	EN							
Kinematic Viscosity at 40 °C (mm^2/s)	2.0-4.5	2.91	1.9-6.0	3.5-5.0	ASTM D445	EN ISO 3104	3.45	4.61	4.48	3.96	4.33	5.0	4.11
Density 15 °C (kg/m^3)	850	839	880	860-900	ASTM D1298	EN ISO 3675	877.6	876.9	864.0	879.1	890	880	876.7
Acid value (mg KOH/g)	-	0.17	Max. 0.50	Max. 0.50	ASTM D664	EN 14104	0.34	0.38	0.28	0.14	0.23	0.41	0.19
Calorific value (MJ/kg)	42-46	45.83	-	35	-	EN 14214	41.442	40.493	40.224	40.427	35.56	37	40.43
Flash Point (°C)	60-80	71.5	Min 130	Min 120	ASTM D93	ISO DIS 3679	165.5	156.5	160.5	160.5	180	208	153
Cold filter plugging point (°C)	-25	-	19	Max.5	ASTM D6371	EN 14214	0.0	-	-	-5.0	-7	-	-
Pour point (°C)	-15 to 5	1.0	-15-16	-	ASTM D97	-	2.0	2.8	3.0	-3.0	-3	6	6
Cloud point (°C)	-35 to 15	2.0	-3-12	-	ASTM D2500	-	2.0	3.0	5.8	-3.0	13	-	7
Copper strip corrosion (3 hours at 50 °C)	1	1	Max 3	Min 1	ASTM D130	EN ISO 2160	1a	1	1	-	1a	-	1a
Sulfur content % (m/m)	0.05	-	Max 0.05	Max 10[a]	ASTM D5354	EN ISO 20846	6.23	13.97	8.01	-	15	16	1.9
Oxidation stability (hours at 110 °C)	-	23.7 h	Min 3 h	Min 6 h	ASTM D675	EN 14112	14.27 h	4.42 h	9.41 h	3.44	0.8	-	1.85
Cetane number	40-55	49.7	Min. 47	Min. 51	ASTM D612	EN ISO 5165	59.5	59.5	59.8	57.9	57.6	65	55
Carbon (% wt.)	84-87	88.5	77	-	-	-	72	78	74.0	-	-	-	-
Hydrogen (% wt.)	12-16	13.5	12	-	-	-	12.2	12.5	11.8	-	-	-	-
Oxygen (% wt.)	0-0.31	0	11	-	-	-	11.80	11.68	11.07	-	-	-	-

[a]mg/kg

2.5. Life cycle cost and sensitivity analysis

The similarity between the physical properties of biodiesel and diesel fuel have made biodiesel as one of promising fuel derived from renewable raw materials and sustainable. Palm oil is the widely available in Indonesia and Malaysia in which these countries produce the largest amount of palm oil as compared to other countries. However, it is believed that the production of biodiesel should not rely on one source of feedstocks due to the unavailability issues that will arise in the long term. Dependency on fossil fuels in today's world is the perfect example to demonstrate this overreliance. Hence, the more variety of feedstocks available for the biodiesel production, the better. The variations in feedstocks for biodiesel from non-edible vegetable oil usually depends on the geographical location of these countries (Kansedo et al., 2009). Although the feedstocks for biodiesel production is varied and are available in large quantities such as Indonesia, Malaysia, Thailand and India, but the commercialization of biodiesel has not been done on a large scale. It is influenced by non-technical factors, for example feedstock prices, taxation, crude oil prices, production cost and environmental impact, which cause delays in the development of biodiesel commercialization as (Ong et al., 2012). Life cycle cost (LCC) is one method that can be used to calculate energy requirements, advantages and disadvantages of a biodiesel feedstock. It can also analyze the environmental impact of biodiesel fuel that was served with the potential for emission reductions, area of cropland required for biodiesel feedstock and the environment carbon payback period. The potential for carbon savings are calculated by multiplying the net emissions avoided by the amount of biodiesel required (Yee et al., 2009). Life cycle cost can analyze how much raw material is needed to meet the energy needs of a country. Life cycle cost can be defined as an economic model to analyze the cost of the industry during the production period as well as its environmental impact.

There are many previous studies that have examined methods for analyzing the life cycle of biodiesel production, cycle costs and environmental impact of feedstocks used on some parts of the world. The summary of several assessment factors for economic indicators on techno-economic assessment of several kinds of feedstocks and production methods is shown in Table 2.5. The investigation of biodiesel production from castor oil was performed by Santana *et al.* (2010). Analysis showed that the production cost is $1.56/liter for 8.6 ktons biodiesel plant using an alkali catalyst (Santana et al., 2010). In addition, other investigations conducted by Yusuf and Kamarudin (2013) using *Jatropha curcas* oil, showed that the biodiesel production cost to be $0.78/liter for 40 ktons biodiesel plants using the supercritical process (Yusuf & Kamarudin, 2013).

The study of biodiesel production from palm oil has been investigated by Ong et al. (2012) and Lozada et al. (2010) by using an alkaline catalyst. The cost from the study of biodiesel production are $0.64/liter and $0.37/liter for the plant's capacity by 50 ktons and 36 ktons, respectively (Lozada et al., 2010; Ong et al., 2012). Other researchers have performed studies by using rapeseed oil for biodiesel production plant with a capacity of 8 ktons by Sotoft et al. (2010). The results showed that the cost of biodiesel is $2.04/liter by using enzyme catalyst (Sotoft et al., 2010) while the research conducted by Lee *et al.* (2011) resulted in the production cost of $1.27/liter by using an alkaline catalyst for a plant capacity of 40 ktons (Lee et al., 2011). The high cost of enzyme catalysts driven up the cost of biodiesel and takes a longer process than alkali catalyst. Furthermore, You et al. (2007) and Haas et al. (2006) studied the production of biodiesel using soybean oil for plant capacity 8 ktons and 36 ktons by using an alkali catalyst and sodium methoxide catalyst (Haas et al., 2006; You et al., 2007). The results indicated the biodiesel production costs are $0.78/liter and $0.53/liter respectively. Besides, Marchetti et al. (2008) and Sakai et al. (2009) investigated the waste cooking oil processed through supercritical process and alkali catalyst for plant capacity of 36

ktons and 7 ktons, respectively. The study shows the biodiesel production cost are $0.98/liter and $0.58/liter, respectively. Supercritical process is not particularly recommended because of its low economic feasibility that requires high energy input to the process (Marchetti & Errazu, 2008; Sakai et al., 2009).

Table 2.5: Comparison biodiesel production cost from several feedstocks.

Feedstock	Plant capacity ton/year	Feedstock cost $/ton biodiesel	Glycerol credit $/ton biodiesel	Biodiesel cost $/liter	Location	Remark	References
Castor oil	8,650	1,156	44.1	1.56	Brazil	Alkali catalyst	(Santana et al., 2010)
Jatropha curcas oil	40,000	1,050.5	145	0.78	Malaysia	Supercritical process	(Yusuf & Kamarudin, 2013)
Palm oil	50,000	1,050	0.0025	0.64	Malaysia	Alkali catalyst	(Ong et al., 2012)
Palm oil	36,000	358	33.5	0.37	Mexico	Alkali catalyst	(Lozada et al., 2010)
Rapeseed oil	8,000	3,042	2,215	2.04	Denmark	Enzyme catalyst	(Sotoft et al., 2010)
Rapeseed oil	40,000	990	147.5	1.27	Canada	Alkali catalysts	(Lee et al., 2011)
Soybean oil	8,000	779	380	0.78	USA	Alkali catalysts	(You et al., 2007)
Soybean oil	36,000	486	35.8	0.53	USA	Sodium methoxide catalyst	(Haas et al., 2006)
Waste canola oil	40,000	990	86.25	0.81	Canada	Supercritical process	(Lee et al., 2011)
Waste cooking oil	36,036	905	67.5	0.98	Argentina	Supercritical process	(Marchetti & Errazu, 2008)
Waste cooking oil	7,260	248	0	0.58	Japan	Alkali catalysts	(Sakai et al., 2009)

The biodiesel production through conventional esterification and transesterification process as well as performance of biodiesel-diesel blends has been widely studied including Malaysia. Table 2.5 shows the comparison of production cost from several feedstocks from the literature. Palm oil and *Jatropha curcas* have been studied in Malaysia only. However, no study found to be working on biodiesel production from crude *Reutealis trisperma* oil by ultrasonic transesterification compared to conventional method. There is no study on techno-economic analysis of the *Reutealis trisperma*

biodiesel, especially in Malaysia, despite its abundance in the Southeast Asian region. The feasibility of *Reutealis trisperma* for industrial production biodiesel in Malaysia will be assessed by life cycle cost model calculation, considering the subsidy and taxation factor in the context of Malaysia.

CHAPTER 3: METHODOLOGY

3.1. Introduction

Based on the studies that have been done in the literature obtained regarding biodiesel production and current research on non-edible feedstocks, the characteristics of the biodiesel fuel and life cycle cost analysis of feedstocks has been determined for the production of biodiesel in the future. Those researches that have been done in the literature are available in thesis, journal articles, books, conference proceedings and reports. This chapter discusses the methodology used for the biodiesel production using conventional transesterification and ultrasonication and analysis of life cycle costs for *Reutealis trisperma* oil. Characteristics of biodiesel properties from *Reutealis trisperma* oil were investigated according to ASTM D6751 and EN 14214 .The life cycle cost of biodiesel for economic and environmental impact are also examined. Further discussion of the methodology will be discussed in the following section. The Figure 3.1 shows the general flowchart of this research completely.

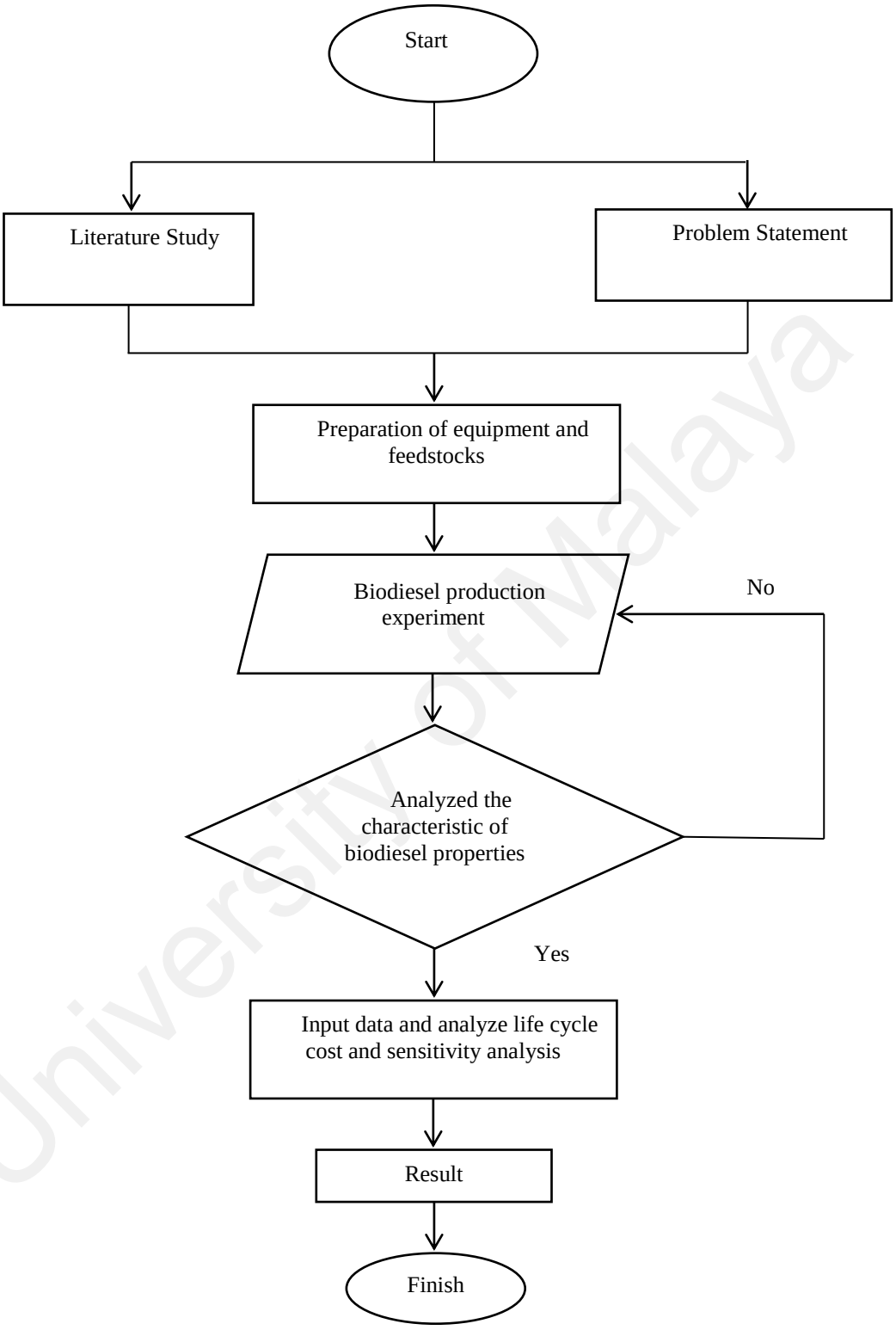
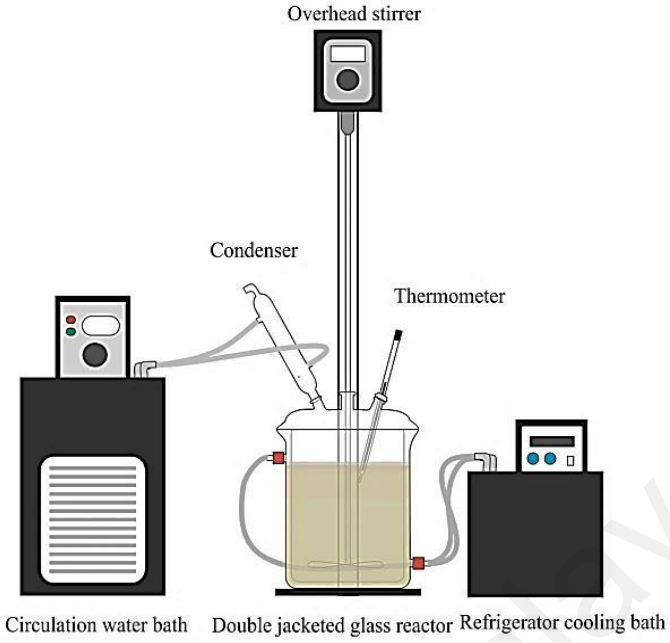


Figure 3.1: Flowchart of research

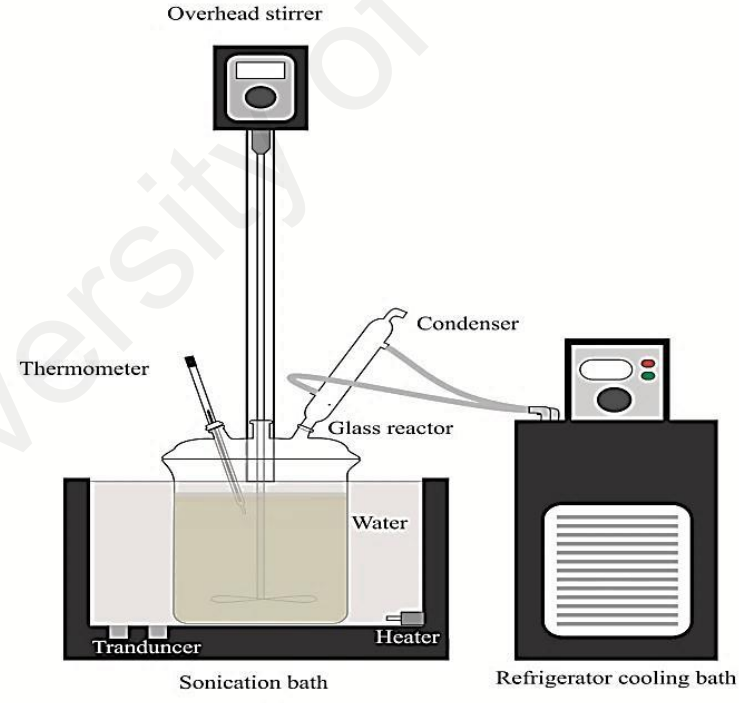
3.2. Materials and experimental setup

Crude *Reutealis trisperma* oil was brought from Indonesia produced by The Department of Chemical Engineering, University of Indonesia, Jakarta, Indonesia. Figure 3.2 shows the crude oil of *Reutealis trisperma*, the fruits of *Reutealis trisperma* can be found around the countryside in Malaysia and Indonesia. All reagents used are methanol, sulfuric acid (H_2SO_4), phosphoric acid (H_3PO_4), potassium hydroxide (KOH), and Whatman filter paper size 150 mm (filter fioroni, France), all were purchased from local suppliers. The equipment used for experimental process of crude *Reutealis trisperma* oil esterification and transesterification process is presented in Figure 3.3. The ultrasonic bath stirrer (Model: Powersonic 410, 500W-40 kHz) with bath size (mm) 300 x 240 x 150 is made by Copens Scientific (M) Sdn. Bhd (Malaysia) and the thermometer was set by using the rubber stand at the neck of the flask.

Figure 3.2: Photo of crude *Reutealis trisperma* oil



(a) Conventional



(b) Ultrasonication

Figure 3.3: The equipment for experimental process of crude *Reutealis trisperma* oil

3.3. Biodiesel production

3.3.1. Degumming of crude oil

The crude oil that has been extracted from the seeds, usually contain impurities, residual water, sap and other impurities. It is necessary to do cleaning and filtration of the crude oil prior to the esterification process. In this stage, a simple method is used for cleaning and filtering of crude *Reutealis trisperma* oil. In this process, 5 vol. % of phosphoric acid (H_3PO_4 20%) is added into the crude *Reutealis trisperma* oil at 60°C with the stirring speed of 1000 rpm for 30 minutes. After that, the process is followed by a simple filtration process for 4-5 hours, there was formation of the gums (phosphatides) from the experiment as seen at the bottom of the flask. The gums are removed manually from degummed *Reutealis trisperma* oil and washed with warm water at temperature 45-50°C. After being washed and separated oil from water, the oil is evaporated using a vacuum pump at 60°C for approximately 20-30 minutes to remove the remaining water in the oil. Figure 3.4 presents the degumming process of crude *Reutealis trisperma* oil.

Figure 3.4: Degumming process of *Reutealis trisperma* oil

3.3.2. Acid-catalyst esterification process

The non-edible oil contains high free fatty acids and this problem often causes soap formation during the conversion process when using alkaline catalyst. Therefore, at this stage, a suitable method for this process is pretreating of the acid catalyst (esterification) before stepping to the transesterification process in order to convert free fatty acids into fatty acid methyl ester through an alkaline catalyst.

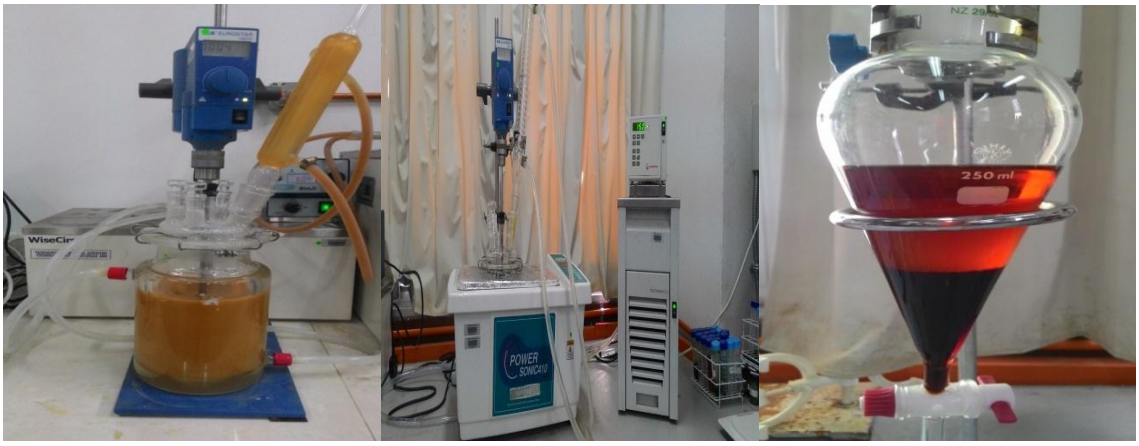
In this research, biodiesel production process for *Reutealis trisperma* oil is made to go through two steps: (1) esterification and (2) transesterification. The main objective of this esterification process is to reduce the amount of free fatty acids contained in crude oil. In this step, 2 % (v/v) of sulfuric acid (H_2SO_4) is added to 500 ml of degummed *Reutealis trisperma* oil. The esterification process is performed under these set of conditions (1) using a reactor bath at stirrer speed: 1000 rpm, (2) the ultrasonic bath, (3) power supply Powersonic 410, 500W (to deliver 100% power) of 40 kHz with stirrer speed at 1000 rpm: at different time parameters (1 hour, 1 hour 30 minutes, 2 hours, 2 hours 30 minutes, and 3 hours), methanol-to oil molar ratio: 60% (by vol.) and temperature: 55°C. Once the reaction of each parameter completed, each product formed is poured into a separation funnel to separate H_2SO_4, methanol and impurities. After 6 hours, H_2SO_4, methanol and impurities presented at the top layer of the oil in the separation funnel and the esterified oil settled at lower layer is also separated. Afterward, the esterified *Reutealis trisperma* oil is evaporated in a rotary evaporator at temperature 60°C for 30 minutes under vacuum conditions to remove water and methanol residues in the esterified oil.

3.3.3. Transesterification process

In this process, the esterified *Reutealis trisperma* oil is pre-heated to 60°C and methanol-to-oil ratio was 60% (by vol.). Then 0.5 wt. % of potassium hydroxide (KOH)

is dissolved into methanol. This methanol and KOH solutions are added in the pre-heated oil at 60°C and the reaction is let to continue for different time parameters: 1 hour, 1 hour 30 minutes and 2 hours. During the esterification process, the oil is stirred constantly at a speed of 1000 rpm using an overhead stirrer for conventional method. Meanwhile, ultrasonic bath is conducted for maximum frequency of 40 kHz with stirrer speed of 1000 rpm and the temperature was constant at 60°C. After the reaction of each parameters completed, methyl ester is poured into each separating funnel in order to separate the glycerol from methyl ester (biodiesel) for approximately 7 hours. The bottom layer is the excess methanol, where impurities and glycerol have been removed at this stage. Then the methyl ester is put into the rotary evaporator at 60°C for 15 minutes to evaporate extra methanol The methyl ester subsequently washed with warm water at 45-50°C for several times before being poured once again into the rotary evaporator at 60-65°C for 30 minutes to remove water completely from biodiesel and then filtered by a filter paper. Figure 3.5 shows the esterification and transesterification process of crude *Reutealis trisperma* oil.

(a) The equipment used for esterification process and esterified oil on the separation funnel



(b) The equipment used for the transesterification process and biodiesel oil on the separation funnel

(c) The rotary evaporator equipment used to evaporate extra methanol in biodiesel

Figure 3.5 (a, b, c): Photo of esterification, transesterification and evaporation process

3.4. Characterization of physicochemical fuel properties

3.4.1. Fatty acid composition

Fatty acid composition from CRTO is identified using gas chromatography (GC). Gas chromatography is a type of chromatography commonly used to analyze and separate vaporable compounds without decomposition. GC can be used to identify compounds contained in the oil. GC can also be used to separate different mixed components (the

relative amount of these components can be determined) or to test the purity of a particular substance. GC is a model gas chromatography equipped with a flame ionization detector (FID). The detector and injector temperature were 250ºC. The temperature was programmed to maintain at 100ºC for 10 minutes until it reaches 220^0C-240^0C with increased rate at 15^0C/min. The gas used is helium gas with high purity. Peak fatty acid methyl esters were identified by comparing the retention time with a known standard.

3.4.2. Properties crude oil and biodiesel

Once the conversion process is completed, then the biodiesel fuel will be tested in accordance with the standard. Table 3.1 shows the equipment used to analyze the chemical properties and physical properties of crude oil and biodiesel. The properties are tested according to ASTM 6751 and EN 14214 standard and every variable is tested three times each (Atabani et al., 2013b; Silitonga et al., 2013b).

Table 3.1: List of the equipment and standard method used for properties test

Property	Equipment	Standard method	Accuracy
Kinematic viscosity	NVB classic (Normalab, France)	ASTM D445	±0.01 mm^2/s
Density	DM40 LiquidPhysics™ density meter (Mettler Toledo, Switzerland)	ASTM D127	±0.1 kg/m^3
Copper strip corrosion	Seta copper corrosion bath 11300-0 (StanhopeSeta,UK)	ASTM D130	-
Flash point	NPM, 440 Pensky-martens flashpoints testers (Nor, Alab, France)	ASTM D93	±0.1 ^{0}C
Calorific value	6100EF Semi auto bomb calorimeter (Perr, USA)	ASTM D240	±0.001 MJ/kg
Cloud and pour	NTE 450 Cloud and pour point tester	ASTM D2500	±0.1 ^{0}C

point	(Normalab, France)		
Acid value	Automation titration rondo 20 (Mettler Toledo, Switzerland)	ASTMD664 and EN 14111	Acid number ± 0.001 mg KOH/g
Sulfur content	Multi EA 5000 (Analytical Jena, Germany)	ASTM D6667	±0.01 ppm

3.4.3. The Fourier transform infrared spectrum

Fourier Transform Infrared (FTIR) spectrometer is the preferred method of infrared spectroscopy. In infrared spectroscopy, the radiation of infrared is passed through the sample. Some of the infrared radiation is absorbed by the sample and partially passed (transmitted). The resulting spectrum is the absorbed and transmitted molecules, creating the former molecules of the sample. Like fingerprints, there are no two molecular structures that can produce the same infrared spectrum. This is what made infrared spectroscopy useful; to identify unknown materials, to determine the quality of the samples and to determine the number of components in the liquid. For characterization of RTME, a FTIR spectrometer (Model: TENSOR 27, Bruker Optics Inc., USA) is used to analyze the content in biodiesel. FTIR output is analyzed by computer software such as OPUS spectroscopic and instruments. An infrared absorption band of FTIR spectra allows one to identify the long-chain fatty acid esters contained in RTME.

3.5. Life cycle cost analysis and sensitivity analysis

3.5.1. Data collection

Data are collected from various sources such as research papers, technical notes, and reports from subject-matter experts as well as the latest market prices, in addition to the data from experimental results. In the case where no specific data on the matter is available, assumptions shall be made using comparable data. Furthermore, sensitivity analysis shall be performed to identify the most important data as well as the effects of variations from the true values. Generally, the basis of studies on the biodiesel production plant shall be based on the production capacity of the plant. A common production capacity value of 50 ktons shall be assumed. Table 3.2 shows the summary of the economic data indicators used in this study for a typical 50 ktons biodiesel plant in Malaysia.

Table 3.2: Summary of economic data and indicators (Ong, 2012)

Input data	Data
Year enacted	2018
Project lifetime (n, year)	20
Discount rate (r, %)	8.0%
Plant capacity (ton/year)	50,000
Feedstock cost, S (%)	2.0%
Feedstock price ($/ton)	50
Operating cost/unit (Or, $/ton/fame)	250
Maintenance cost/unit (Or, $/ton/fame)	2.50%
Yield of biodiesel (fame) conversion	98%
Feedstock price, feedstock consumption (FP-FU, tons)	57,471
Depreciation model (d, %)	10%
Replacement cost ($ million)	10,000,000
Glycerol conversion factor from feedstock oil (Gcf, kg/ton)	100
By product price ($/ton glycerol)	300

Glycerol price by product (tons)	5,747.13
By product price increase ratio (%)	0%
Tax (%)	15%
Subsidy for biodiesel cost ($/liter) G 1	0.10
Subsidy for biodiesel cost ($/liter) G 2	0.18
Diesel (fossil) selling price ($/liter)	0.58
Biodiesel selling price for first to tenth year ($/liter)	0.47
Biodiesel selling price for eleven to till the end ($/liter)	2
Density (kg/m^3)	892
Calorific value of biodiesel (MJ/kg)	40.10
Oil yield biodiesel feedstock (kg/ha)	3273

3.5.2. Life cycle cost

Life cycle costs of the plant may be used to evaluate the economic benefits of the plant. Sometimes referred to the literature as total ownership cost, the life cycle cost must consider all costs associated with the plant from its inception to decommissioning. For our purpose, the life cycle costs of the plant for the production of biodiesel oil from *Reutealis trisperma* may be divided into six parameters: initial capital cost (CC), operating cost (OC), maintenance cost (MC), feedstock costs (FC), salvage value (SV), and by-product credits (BP), and all the parameters are related as the following equation (Mahlia et al., 2011; Ong, 2012; Shafie, 2015):

$$LCC = CC + OC + MC + FC - SV - BP \quad (3.1)$$

Recently, present value calculation is widely used in the economics and business to compare cash flows at different times. By applying the given approach, the present value model for the life cycle cost is presented as follows:

$$LCC = CC + \sum_{i=1}^{n} \frac{OC_i + MC_i + FC_i}{(1+r)^i} - \frac{SV}{(1+r)^n} - \sum_{i=1}^{n} \frac{BP_i}{(1+r)^i} \quad (3.2)$$

Where *r* is the interest rate value

Present worth factor

The present value factor (*PWF*) is the total estimated value of the project that is currently collected from future cash flows. The feasibility of investment in a biodiesel production plant is determined by using the present worth factors (*PWF*) with a given discount rate. For years *i*, PWF is given as follows (Mahlia et al., 2011):

$$PWF = \frac{1}{(1+r)^i} \quad (3.3)$$

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

$$CPW = \sum_{i=`}^{n} \frac{1}{(1+r)^i} \quad (3.4)$$

$$CPW = \frac{(1+r)^n - 1}{r(1+r)^n} \quad (3.5)$$

Capital cost

The capital cost of the plant includes the initial costs for installation of the plant to allow for its operation; from the cost of the land, building cost, equipment, testing etc. Normally, the capital cost is dependent on the biodiesel production plant capacity. For

this work, capital cost is approximated based on the reference (Ong, 2012; Shafie, 2015), whereby three (3) possible initial capital costs may be considered based on the production capacity of the plant; maximum CC_{high}, average CC_{avg}, and minimum CC_{low} initial capital costs of the biofuel plant. These 3 possible initial capital costs of the biofuel production plant are given as follows (Ong, 2012):

$$CC_{high} = -517.76 \times PC^2 + 252928 \times PC + 3446300 \quad (3.6)$$

$$CC_{avg} = -430.13 \times PC^2 + 205235 \times PC + 2696000 \quad (3.7)$$

$$CC_{low} = -342.49 \times PC^2 + 157542 \times PC + 1945700 \quad (3.8)$$

Operating cost

The operating cost includes factory costs, transportation costs, utilities costs, administrative expenses, laboratory services, supervision costs, labor costs, and all other material and energy flows excluding the cost of feedstocks. Costs for waste and sewage sludge treatments are also included in the operating cost. The operating cost consists of fixed and variable operating costs and by assuming that the plant is producing biodiesel at its maximum production capacity, the operating cost per ton of produced biodiesel may be introduced. Furthermore, assuming that, the operating cost per ton of the plant are fixed throughout its project lifetime, the total operating costs (OC) throughout the project lifetime by using present value calculations, may be given as follows:

$$OC = \sum_{i=1}^{n} \frac{OR \times PC}{(1+r)^i} \quad (3.9)$$

Maintenance cost

Service and periodic maintenance costs may be taken to be a given percentage (*MR*) of the initial capital cost (*CC*) and both are assumed to be constant for the whole project life span. The total maintenance costs (*MC*) throughout the project lifetime using present value calculations may be given as follows:

$$MC = \sum_{i=1}^{n} \frac{MR \times CC}{(1+r)^i} \quad (3.10)$$

Feedstock cost

Annual feedstock consumption (*FU*) of the plant is determined by the capacity of the plant (*PC*) after accounting for the biodiesel conversion efficiency (*CE*) and through that, the feedstock is converted into biodiesel. Further, it is assumed that annual feedstock consumption (*FU*) is constant throughout the project lifetime and is given by:

$$FU = \frac{PC}{CE} \quad (3.11)$$

The total feedstock costs (*FC*) throughout the project lifetime, using present value calculations may be given as follows:

$$FC = \sum_{i=1}^{n} \frac{FP \times FU}{(1+r)^i} \quad (3.12)$$

Salvage value

The salvage value is the remaining value of components and assets of the project at the end of its lifetime; however, instead of using the initial capital cost as the basis for the calculation, the cost of replacing the plant and its assets (i.e., the replacement cost (*RC*)) is used. This is because intuitively the salvage value of the plant at the end of its lifetime is determined by the capital cost at the end of the project lifetime after discounting for depreciations. A constant annual depreciation rate (*d*) is assumed in this study. The salvage value, using present value calculations, may be estimated by the following equation:

$$SV = RC \times (1 - d)^{n-1} \tag{3.13}$$

Therefore, the current value of the salvage cost is expressed by the following equation:

$$SV_{pv} = \sum_{i=1}^{n} \frac{RC \times (1 - d)^{n-1}}{(1 + r)^n} \tag{3.14}$$

By-product credits

Glycerol is a by-product of the biodiesel production process. Although it is unusable for biodiesel use, it may be further converted into different products such as fuel oxygenates (additive), propylene glycol (liquid alcohol that is used as a solvent, in antifreeze, in food, plastics, and perfume industries), reforming syngas and glycerol carbonate. The authors in reference (Pagliaro et al., 2007) stated that glycerol can be converted and used as a solvent and anti-freeze in pharmaceutical applications and numerous other products through catalytic conversion. As such, glycerol may actually be sold further as a useful by-product. Of course, the receivable from the sale of glycerol, as a by-product of the plant, is determined by the actual amount of glycerol

that is produced. Given a glycerol conversion factor of *GCF*, the by-product credit obtained from the sale of glycerol over the project lifetime, using present value calculations, may be given as:

$$BP = \sum_{i=1}^{n} \frac{GP \times GCF \times FU}{(1+r)^i} \tag{3.15}$$

Payback Period

The feasibility and viability of the plant may be evaluated using a simple method called the payback period (*PP*). To put it simply, the payback period may be interpreted as the time required to gain a financial return from the plant equal to the initial investment costs for the plant. Taking the initial investment costs of the plant as the initial capital cost (*CC*), the payback period is calculated as the ratio of capital cost to net annual income obtained from the plant and given by the following equation (Mahlia et al., 2011):

$$PP = \frac{CC}{TBS - TPC - TAX} \tag{3.16}$$

Whereby,

$$TBS = \frac{BFP \times PC}{\rho} \tag{3.17}$$

$$TPC = 1.1 \times \frac{LCC}{n} \tag{3.18}$$

$$TAX = (TBS - TPC) \times TR \tag{3.19}$$

Total biodiesel cost

The Annual Total Production Cost (*TPC*) of the biodiesel consists of the life cycle cost distributed over the life of the project of n years and the reasonable profit margin. Assuming a profit margin of 10% over the distributed *LCC*, the annual total production cost (*TPC*) of the biodiesel may be calculated as follows:

$$TPC = 1.1 \times \frac{LCC}{n} \tag{3.20}$$

Final biodiesel unit cost

It is also important to determine the minimum sales price per unit of biodiesel fuel that would cover the costs of producing the biodiesel as well as provides the required profit margin. In this paper, the profit margin is taken to be 10%. This value is equivalent to the final biodiesel cost (*FBC*) per unit, which is given by the ratio of the annual total production cost (*TPC*) of the biodiesel to the annual total amount of biodiesel that is produced from the plant. The final biodiesel cost (*FBC*) is given by:

$$FBC = \frac{TPC \times \rho}{PC} \tag{3.21}$$

3.5.3. Potential fuel saving

Biodiesel and diesel fuels have some dissimilarity in heating value or calorific value. Therefore, the biodiesel to diesel fuel substitution ratio is expressed as the following equation:

$$SR_w = \frac{HVG}{HVB} \tag{3.22}$$

The sum of the diesel fuel substitution is a function of the yearly diesel fuel consumption with a substitution ratio, which is presented by applying the equation below:

$$GR_i = \eta \times GC_i \tag{3.23}$$

The total biodiesel required for replacing the diesel fuel is estimated by the diesel fuel substitution multiplied by the biodiesel to diesel fuel substitution ratio which is shown in the equation below:

$$BC_i = GR_i \times SR_w \tag{3.24}$$

The fossil diesel fuel potential energy savings can be calculated by using the following equation:

$$TDS = \sum_i^n GR_i \times EC \tag{3.25}$$

3.5.4. Sensitivity analysis

The key variables such as life cycle cost (*LCC*), payback period (*PP*) and final biodiesel unit cost (*FBC*), which form the basis of determining the feasibility/viability of the project and its economic benefits, are calculated based on key assumptions and projections. Some of the assumptions made are for the price of feedstocks (*FP*), replacement cost (*RC*) of the plant, operating rate (*OR*), etc. Uncertainty in the market, due to demand/supply, technologies, and other factors, may cause some of these values to vary from these key assumptions and projections, such that it may change the outcome and performance of the project.

Sensitivity analysis may be used to assess the effect of variations in key assumptions and projections, on the projected performance of the project. For the sensitivity analysis, there are several important variables that must be considered: feedstock prices, initial capital costs, operating costs, and discount rate. The most important factor of these variables is the feedstock price. It is expected that the price of the feedstock will follow its market value and will be sensitive to other related markets such as energy supply/demand; the market value of its substitute. Generally, the price of feedstock shall rise if the demand exceeds the supply and vice-versa. The increase in demand for the feedstocks may be caused by several factors, such as an increase in demand of the biodiesel and limited supply of crude oil, and the price increment on the feedstock will act as the throttle to control biodiesel production. Similarly, a reduction in the supply of the feedstock, caused by, for example natural disasters, may also increase the price of feedstock. The feedstock used in this study comes from *Reutealis trisperma*, a second-generation feedstock and hence, it is comparatively stable in price as it does not need to compete with the food market, unlike the first-generation feedstock.

3.5.5. Biodiesel taxation and subsidy scenarios

Policies on taxation and subsidies on a biodiesel product and its substitutes have an influence on the final cost of biodiesel in the country. Analyses are normally performed to compare the effect of different taxation and subsidy scenarios on the final price of biodiesel, to give insights to policy-maker on ways to encourage the use of biodiesel. These analyses may be based on the adoption of different policies; different tax rates, total tax exemption, and different costs of subsidies. To stimulate the biodiesel market, it may also include studies on the effect of variation in the values of important input variables, such as feedstock price and the price of its substitutes, to determine whether or not policy intervention is required. Like other new technologies, subsidies may be inevitable for biodiesel to be on par with the fossil diesel price. The subsidy cost is usually selected based on the current subsidy cost of its substitute; namely the subsidy of diesel fuel in certain countries. The subsidy for biodiesel cost G1 and G2 is set to be \$0.10/liter and \$0.18/liter, respectively. Subsidies have been chosen based on the current subsidy cost of diesel and gasoline fuels in Malaysia. There is a difference in energy content between biodiesel and diesel fossil fuels. Therefore, the substitution ratio of biodiesel to diesel fuel based on Eq. 3.22 has been calculated for consideration.

3.5.6. Potential environmental impact

In this study, the potential environmental impact of the biodiesel plant on emissions and crop land use for biodiesel feedstocks is assessed.

Total carbon saving

Biodiesel is comparatively cleaner when compared to fossil diesel, in terms of carbon emission. This is one of the reasons for active researchers in this field and the position of biodiesel as one of the possible efficient substitutes for fossil diesel. To measure the benefits of adopting biodiesel, total carbon saving (*TCS*) may be used; which is defined as the amount of carbon emission that may be avoided by substituting fossil diesel with biodiesel. Total carbon saving (*TCS*) is given by the following equation:

$$TCS_i = TCD_i - TCB_i \tag{3.26}$$

Where by,

$$TCD_i = DR_i \times EFD \times HVG \tag{3.27}$$

$$TCB_i = BC_i \times EFB \times HVD \tag{3.28}$$

Cropland needed

The use of feedstock for biodiesel production requires usage of cropland which could otherwise be utilized for other purposes. It is important to estimate the cropland needed (*CLR*) for the feedstock which can be calculated simply as the ratio of the feedstock needed to facilitate the fuel substitution to the feedstock yield per acre of cropland

$$CLR = \frac{BC \times 1000}{OY} \tag{3.29}$$

Ecosystem carbon payback period

The ecosystem carbon payback period is the period from the commencement of the project to the point in time where the overall carbon balance equals the carbon storage before the project. It may be estimated by dividing the difference between the carbons stock from converting the natural land into biodiesel feedstock cropland with the yearly carbon savings by utilizing the biodiesel fuel. Thus, the ecosystem carbon payback period (*CPP*) may be calculated as follows:

$$CPP = \frac{LSC - BCC}{TCS/CLR} \tag{3.30}$$

The operation lifetime of the plant is set to 20 years including one year from construction to starting the plant. All initial capital cost is considered to be paid by private investment and during the entire project, the plant is assumed to operate 100% capacity. Properties of biodiesel and diesel fuels such as density, related conversion yield and calorific value are shown in Table 3.2 summary of economic data and indicators, the input data for this study are summarized in the Table. The life cycle cost calculation and sensitivity analysis of *Reutealis trisperma* biodiesel fuel including production of feedstock as well as biodiesel production via ultrasonic transesterification process will be discussed in the next chapter.

CHAPTER 4: RESULT AND DISCUSSION

4.1. Introduction

This chapter contains the results and discussion for the production of biodiesel and life cycle cost analysis from *Reutealis trisperma* as biodiesel. The results of laboratory experiments from crude oil for biodiesel production of *Reutealis trisperma* oil are described in this chapter. In addition, the life cycle costs of biodiesel production from *Reutealis trisperma* biodiesel are analyzed. Then, the costs of subsidies for replacing diesel with biodiesel fuel are presented. Finally, the potential fuel savings and reduction in the emission and environmental impact is calculated and presented in the following discussion.

4.2. Properties of crude *Reutealis trisperma* oil

The physicochemical properties and fatty acid composition of crude *Reutealis trisperma* such as the acid value, density, viscosity at 40ºC and flash point are analyzed and compared with other non-edible oil as presented in Table 4.1 (Silitonga et al., 2013b; Silitonga et al., 2013c). The test results show that the acid value and viscosity measured are the highest among existing result in literature which are 44.681 mg KOH/g and 76.927 mm^2/s, respectively. In the other hand, density and flash point obtained are 934.5 kg $/m^3$ and 226.5 ^{0}C, respectively. The fatty acid composition of crude *Reutealis trisperma* oil (CRTO) has shown that the primary composition are palmitic acid, oleic acid and linoleic acid which are 13.1 %, 16.1 % and 18.7 %, respectively. As compared to CCPO, CSFO and CCIO have shown that similar dominant compositions are linoleic acid (39.7 %, 9.1%, 24.7%), palmitic acid (19.2%, 17.7%, 14.7%) and oleic acid (17.4%, 6%, 46.1%), respectively (Silitonga et al., 2013b). The crude *Reutealis trisperma* oil contains about 19.5 % saturated fatty acids and 35.3% of unsaturated fatty acids. The total fatty acid determined in crude *Reutealis trisperma* oil is 54% and the

rest is undetected. Therefore, a two-stage catalyst process is required to produce biodiesel fuel from *Reutealis trisperma* crude oil.

Table 4.1: The properties and fatty acid composition of crude *Reutealis trisperma* oil and compare with other non-edible oils

Properties	**CRTO[a]**	**CCPO** (Silitonga et al., 2013b)	**CSFO** (Silitonga et al., 2013c)	**CCIO** (Ong et al., 2014b)
Acid value (mg KOH/g)	44.68	16.80	0.36	44.0
Kinematic viscosity at 40 ^{0}C (mm^2/s)	76.93	34.45	92.64	71.98
Flash point (^{0}C)	236.5	170.5	158.0	221.0
Density at 15 ^{0}C (kg/m^3)	934.5	905.2	937.0	896.0
Fatty acid composition	% wt.	% wt.	% wt.	% wt.
C12:0 (lauric acid)	0.1	0.1	0.1	0.1
C14:0 (myristic acid)	0.2	0.1	0.2	0.1
C16:0 (palmitic acid)	13.1	19.2	17.7	14.7
C16:1 (palmitoleic acid)	0.2	0.3	0.2	0.3
C18:0 (stearic acid)	5.8	2.6	4.7	13.2
C18:1 (oleic acid)	16.1	17.4	6.0	46.1
C18:2 (linoleic acid)	18.7	39.7	9.1	24.7
C18:3 (linolenic acid)	0.1	1.5	0.7	0.2
C20:0 (arachidic acid)	0.2	0.5	2.3	0.8
C20:1 (Paullinic acid)	0.2	-	-	-
C24:0 (Lignoceric acid)	0.1	-	-	-

[a] Analysis results

On the other hand, the fatty acid composition of crude *Reutealis trisperma* oil and other non-edible crude oils, such as *Ceiba pentandra*, *Sterculia foetida*, and *Calophyllum*

inophyllum, shown in Figure 4.1 have almost the same dominant levels of fatty acids, linoleic acid, oleic acid, stearic acid, and palimitic acid.

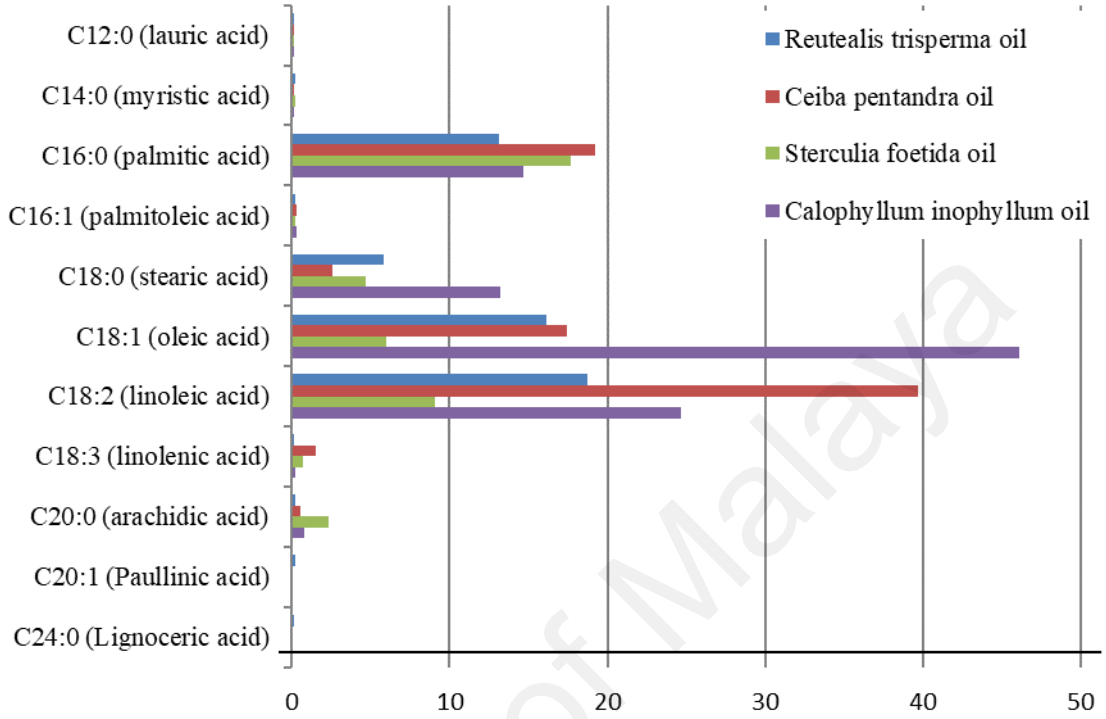


Figure 4.1: Fatty acid composition of *Reutealis triperma* oil and compare to *Ceiba pentandra, Sterculia foetida,* and *Calophyllum inophyllum*

4.3. Fourier transform infrared spectrum of the *Reutealis trisperma* biodiesel

Fourier transform infrared spectrum (FTIR) is one technique that can be utilized to overcome the problem of the quantification and identification in material substances such as fuel, chemistry and the environmental chemical composition (Dharma et al., 2016; Pereira et al., 2006; Sedman et al., 2000). FTIR is commonly used because of its cost, speed and quality screening considerations. This method is called as technique of molecular "fingerprint". The FTIR analysis of the *Reutealis trisperma* biodiesel is presented in Figure 4.2. As can be seen in Table 4.2, the FTIR results of the *Reutealis trisperma* biodiesel such as wave number, group attribution, absorption intensity and vibration type of the absorption peaks have been detected. The results show that the

biodiesel from *Reutealis trisperma* comprises long chain fatty acid esters. The spectrum of the biodiesel product in transesterification is similar to chemical precursors (refined oil), where C=O stretching is 1741 cm^{-1} and the peak is located in the region 1800-1700 cm^{-1}. This is a spectrum of typical ester, it is usually encountered in FAME and oil refined products (Dharma et al., 2016; Soares et al., 2008). In the range area of 1700-700 cm^{-1}, biodiesel from *Reutealis trisperma* showed a peak at 1244 cm^{-1} corresponds to the bending vibration −CH3 which is known as "fingerprint" which is a major region of the spectrum (Rabelo et al., 2015).

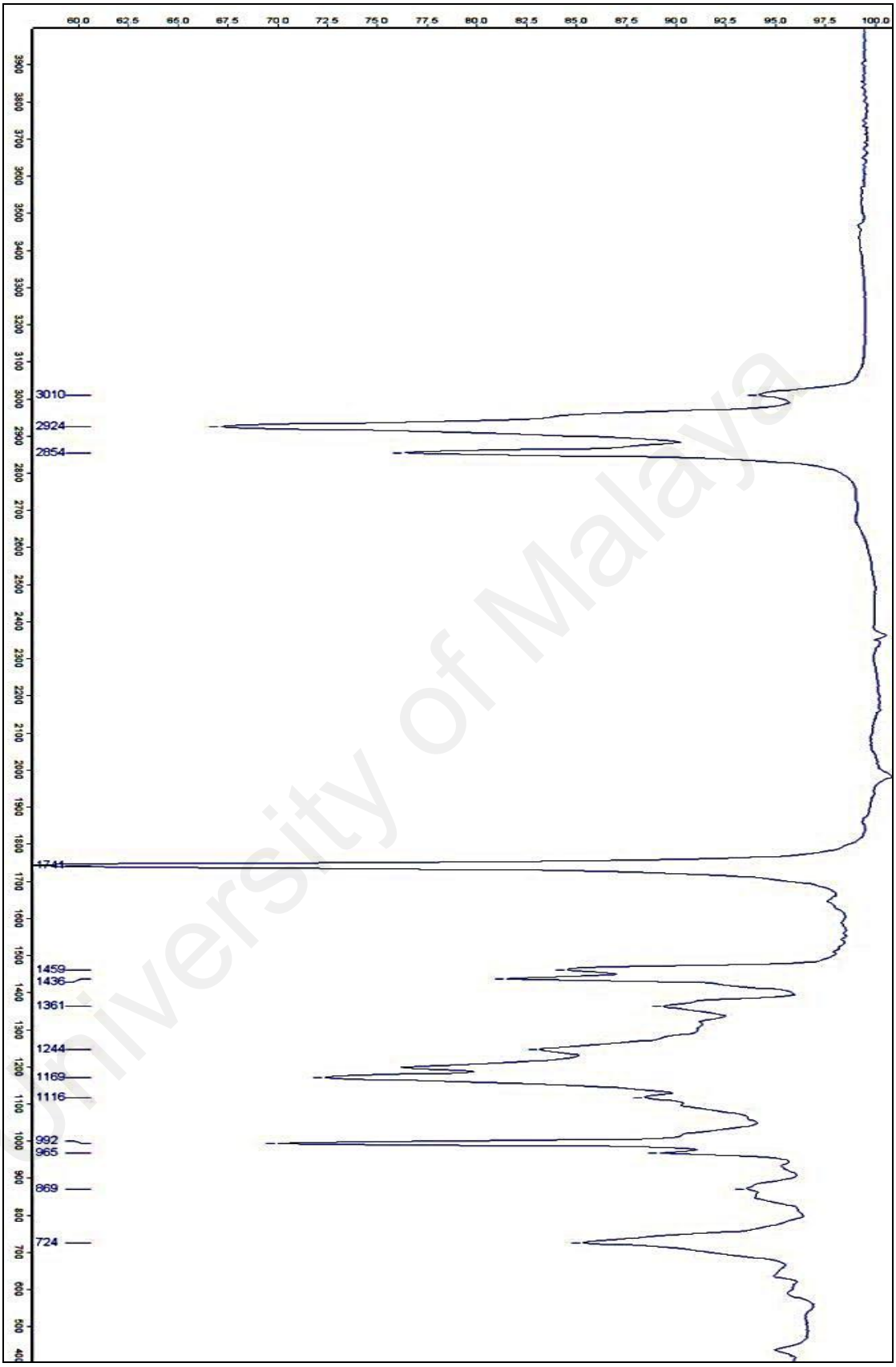


Figure 4.2: Fourier transform infrared spectrum of the *Reutealis trisperma* biodiesel

Table 4.2: The Fourier transform infrared spectrum of the *Reutealis trisperma* biodiesel

Wavenumber (cm^{-1})	Group attribution	Vibration type	Absorption intensity
3010	=C-H	Asymmetric stretching vibration	Weak
2924	=C-H	Asymmetric stretching vibration	Strong
2854	$–CH_2$	Symmetric stretching vibration	Strong
1741	–C=O	Stretching	Strong
1459	$–CH_2$	Shear-type vibration	Weak
1244	$–CH_3$	Bending vibration	Weak
1169	C–O–C	Anti-symmetric stretching vibration	Middling
992	C–O–C	Anti-symmetric stretching vibration	Weak
724	$–CH_2$	Plane rocking vibration	Weak

4.4. Characterization of biodiesel

4.4.1. Physicochemical properties of *Reutealis trisperma* biodiesel

The physicochemical properties of *Reutealis trisperma* biodiesel produced with optimum result in the shortest time from esterification and transesterification process by using the ultrasonic bath stirrer method is summarized in Table 4.3. These properties of *Reutealis trisperma* biodiesel are produced through an esterification process of 1 hour at temperature 55°C using 2 % v/v of sulfuric acid (H_2SO_4), methanol-to-oil ratio: 60%, agitation speed: 1000 rpm and transesterification process of 1 hour 30 minutes at temperature 60 °C using 0.5 wt. % of catalyst Potassium hydroxide (KOH), methanol-to-oil ratio: 60%, agitation speed: 1000 rpm.

The physicochemical properties of *Reutealis trisperma* methyl ester (RTME) are compared with other biodiesel, which is listed in Table 4.3 (Holilah et al., 2015; Ong et al., 2014a; Silitonga et al., 2013b; Silitonga et al., 2013c). It is found that most properties of RTME biodiesel fulfilled the ASTM D6751 and EN 14214 standard except for kinematic viscosity. The kinematic viscosity of RTME is 6.48 mm^2/s which relatively higher than other biodiesel, but slightly lower than previous work (Holilah et al., 2015). According to Holilah et al. (2015) the viscosity for RTME, SFME, CIME and CPME obtained were 6.71 mm^2/s, 3.96 mm^2/s, 3.45 mm^2/s, and 4.61 mm^2/s, respectively (Holilah et al., 2015). The result shown exceeded the two standards mentioned. This is due to the presence of triglycerides as a by-product from unreacted *Reutealis trisperma* oil on transesterification process, thus affecting the viscosity of the biodiesel.

Furthermore, the density limit was 880 kg/m^3 at 15 °C for ASTM D6751 and 860-900 kg/m^3 at 15 °C for EN 14214 biodiesel standards. The density results are 892 kg/m^3, 879.1, 877.6, and 876.9 for RTME, SFME, CIME and CPME, respectively. The obtained flash point result is higher compared to other biodiesels, which are 206.5 °C, 160.5 °C, 165.5 °C, and 156.5 °C for RTME, SFME, CIME and CPME, respectively. Furthermore, the calorific values are 40.098 MJ/kg, 40.427 MJ/kg, 41.442 MJ/kg and 40.493 MJ/kg for RTME, SFME, CIME and CPME, respectively which fall within ASTM and EN biodiesel standards. The obtained acid value is 0.26 mg KOH/g, 0.14 mg KOH/g, 0.34 mg KOH/g, and 0.38 mg KOH/g for RTME, SFME, CIME and CPME, respectively, which are in range of ASTM D6751 and EN 14214 biodiesel standards which it should be lower than 0.5 %.

Table 4.3: Physicochemical properties *Reutealis trisperma* biodiesel and other biodiesels

Property	Unit	ASTM D6751 Limit	EN 14214 Limit	RTME[a]	RTME (Holilah et al., 2015)	SFME (Silitonga et al., 2013c)	CIME (Ong, 2012)	CPME (Silitonga et al., 2013e)
Kinematic viscosity at 40 °C	mm^2/s	1.9–6.0	3.5–5.0	6.48	6.71	3.96	3.45	4.61
Density at 15 °C	kg/m^3	880	860–900	892	887	879.1	877.6	876.9
Flash point	°C	Min. 130	Min. 120	206.5	148	160.5	165.5	156.5
Pour point	°C	-15 to 16	-	-2	−15	-3.0	2.0	2.8
Cloud point	°C	-3 to 12	-	-1	-13	-3.0	2.0	3.0
Calorific value	MJ/kg	–	35	40.098	38.55	40.427	41.442	40.493
Acid value	mg KOH/g	0.5 max.	0.5 max.	0.26	0.41	0.14	0.34	0.38
Copper corrosion strip	–	3 max.	–	1b	-	-	1a	1
Sulfur content (S 15 grade)	Ppm	15 max.	-	14.85	-	-	6.23	13.97

[a] Analysis results

4.4.2. Effect of esterification process on acid value vs time

The high percentages of FFA (free fatty acid) content and water in vegetable oil may affect the conversion process to biodiesel due to saponification reaction that produce soap when reacted with base catalysts. Therefore, vegetable oils must go through the esterification process to reduce the FFA content in the oil and to prevent saponification reactions. For the conversion process of crude oil into biodiesel to run smooth, the FFA content in the oil should be less than 1.0%. The higher the fatty acids present in the vegetable oils, the higher catalyst concentration required in the esterification process. According to Nurjannah et al. (2015), if the acid value, reflecting the free fatty acid, greater than 1, more alkali catalyst is required to neutralize the FFA content (Nurjanah

et al., 2015). Holilah et al. (2015) reported that the FFA content is about 2.4 % in *Reutealis trisperma* oil. However, this kind of oil can be esterified by using conventional methods with an acid catalyst but it would require a longer reaction time which is uneconomical. It has been shown that Holilah et al. used 3 wt.% acid catalyst (H_2SO_4) for 2 hours in the esterification process (Holilah et al., 2015) whereas, the production of biodiesel from *Oreochromis niloticus* oil using ultrasonication method performed by Santos et al. (2009) required only 90 min for esterification process at 30 °C with 2% w/w sulfuric acid. The esterification process is done by using an ultrasonic bath (dimensions: 14 x 24 x 9 cm) at a frequency of 40 kHz. Based on this research, the conventional stirring process requires more catalyst and longer reaction time to obtain the same results as the ultrasonic process.

The trend of acid value versus time from esterified *Reutealis trisperma* oil using conventional and ultrasonic bath stirrer method is presented in Figure 4.3. As illustrated in Figure 4.3 the ultrasonic bath stirrer method had the lowest acid value after 1 hour of esterification process. The observed acid value was 0.476 mg KOH/g. By increasing the time of esterification for ultrasonic bath stirrer method to be more than 1 hour, the acid value will increase. Meanwhile, for the conventional method, the lowest acid value is found after 3 hours of esterification process. The obtained acid value was 0.367 mg KOH/g. From experimental result, it can be seen that the lowest acid value with the shorter time for the ultrasonic bath stirrer method is found after 1-hour process, whereas, the conventional method spent up to 3 hours for the esterification process to produce the lowest acid value.

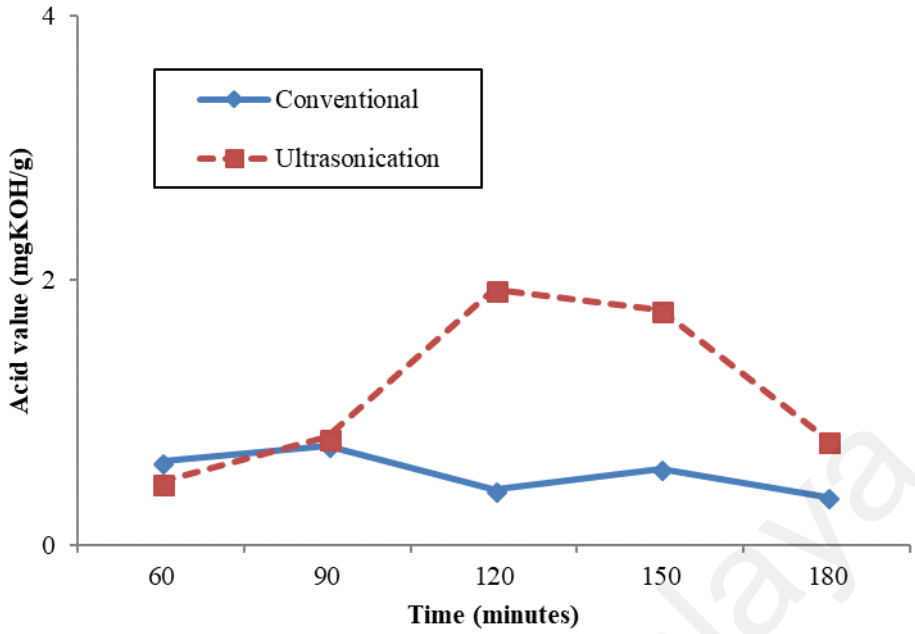


Figure 4.3: Effect of esterification process to acid value of *Reutealis trisperma*

4.4.3. Effect of transesterification process on acid value

Maghami et al. (2015) has reported the biodiesel production from waste fish oil (WFO) using ultrasonic and conventional methods. From the results of the experiment, the acidity of WFO while was 10.5 mg KOH/g can be reduced to 0.65 mg KOH/g through ultrasonic method for 1-hour reaction time and 1 wt. % catalyst at temperature of 55 °C. It is mentioned that conventional method takes 3 hours with catalyst 5 wt.% to get the similar result. Although this type of oil can also be processed via esterification-transesterification method by using conventional mechanical stirrer and acid catalyst, but the required amount of catalyst and methanol is much more and longer reaction time is required for making the production process which both are undesirable (Maghami et al., 2015). In this study, the experiments have been conducted with 0.5 wt. % potassium hydroxide (KOH) as an alkaline catalyst at temperatures of 60 °C and the time varied for an hour, 1 hour 30 minutes, and 2 hours to compare the conventional and ultrasonication method. The trend of acid value versus time from *Reutealis trisperma* biodiesel is presented in Figure 4.4. As can be seen in Figure 4.4, the ultrasonic bath

stirrer method shows the shortest time and lowest acid value after 1 hour 30 minutes of the transesterification process, with the obtained acid value is 0.268 mg KOH/g. Meanwhile, for ultrasonic method, increasing the time of the transesterification process up to 2 hours will increase the acid value. However, in the conventional method, it needs up to 2 hours to approach the acid value of ultrasonic method; the observed acid value is 0.273 mg KOH/g after 2-hour transesterification process.

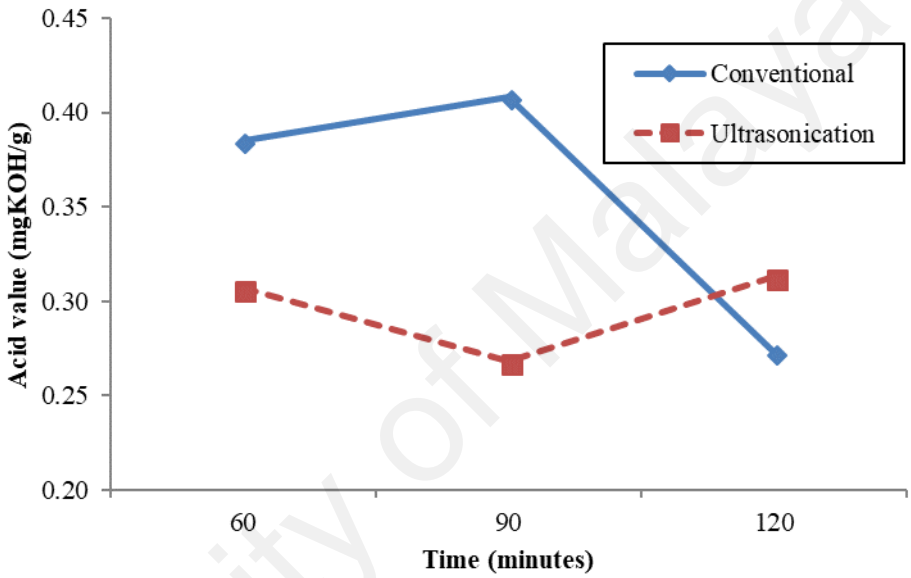


Figure 4.4: Effect of transesterification process to acid value of *Reutealis trisperma*

4.4.4. Effect of transesterification process on viscosity vs time

Holilah et al. (2015) investigated the *Reutealis trisperma* oil for biodiesel production using conventional method through esterification and transesterification process with a constant stirring speed. They found that the kinematic viscosity of *Reutealis trisperma* biodiesel is 6.71 mm^2/s and it is believed the presence of triglycerides produced as a by-product from the unreacted *Reutealis trisperma* oil is the one affecting the kinematic viscosity of the biodiesel (Holilah et al., 2015). In another study, Teixeira et al. (2009) conducted a comparative analysis of biodiesel from beef tallow using conventional and

ultrasonic methods. In literature, beef tallow has a high kinematic viscosity. Therefore, the effect of ultrasonic through transesterification has been investigated. The conventional transesterification process is carried out for 1 hour at 60 °C with 600 rpm stirring speed. In addition, ultrasonic transesterification with maximum power of 400W-24 kHz for 70 s at temperature 60 °C is performed, and the experimental results show the viscosity of biodiesel from beef tallow is 4.89 mm^2/s and 4.66 mm^2/s for conventional and ultrasonic transesterification method, respectively. From the above results, it can be seen that the ultrasonic method and conventional methods have little effect on the viscosity in biodiesel (Teixeira et al., 2009). In this work, the effects of transesterification process using conventional and ultrasonic bath stirrer methods on the viscosity versus time for *Reutealis trisperma* biodiesel is not very significant. From Figure 4.5, it can be seen that after the transesterification process for 2 hours, the conventional method shows the lowest number of viscosity of 6.28 mm^2/s. Meanwhile, for ultrasonic bath stirrer method, the lowest number of viscosity after 2 hours of transesterification process was 6.37 mm^2/s. From the experiment, it was found that the viscosity of *Reutealis trisperma* biodiesel is slightly above the limit of ASTM D6751 and EN 14214 standards which is acceptable.

The transesterification on biodiesel from vegetable oils resulted in viscosity to be approximately twice of that from diesel fuel. Higher molecular weight and longer molecular structure in biodiesel causes the high viscosity in biodiesel in addition to the main element of unsaturated fatty acid in *Reutealis trisperma* such as linoleic acid and oleic acid. Long-term use of pure biodiesel with high viscosity may disrupt diesel engine operations, but biodiesel-diesel mixtures are expected to be an alternative way to improve the biofuel parameters of the *Reutealis trisperma*. Viscosity affected by the fatty acid found in vegetable oils, especially non-edible oils, can be overcome by mixing biodiesel-diesel or biodiesel-biodiesel from other feedstocks which can reduce

the viscosity to meet the required standards. Candeia et al. (2008) reported the effect of soybean biodiesel content on the biodiesel-diesel mixture. From the results of the experiment, all biodiesel-diesel blends show decreased viscosity and fulfill the requirements of viscosity standard either in B5 mixture (5%) or B50 (50%) (Candeia et al., 2009).

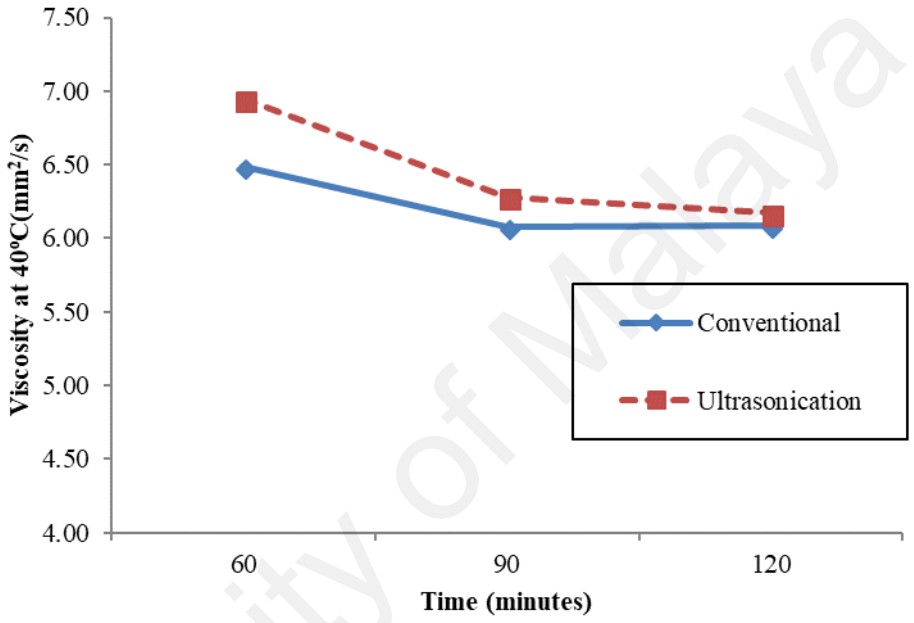


Figure 4.5: Effect of transesterification process on viscosity of *Reutealis trisperma*

4.4.5. Effect of the transesterification process on yield

Ultrasonic method will reduce the process time with higher yield as compared to conventional method, based on the fact that ultrasonic increases the interaction among the phases due to the ultrasonic jet which consequently increased the reaction (Takase et al., 2014). Besides, previous study of comparative conventional and ultrasonic methods of biodiesel production from non-edible Mahua oil has been done by Bahadur et al. (2015). The biodiesel production is performed using conventional and ultrasonic methods through a two-steps transesterification with 0.75% v/v catalyst potassium hydroxide and a 1:5 oil to methanol ratio at 45 °C temperature. The magnetic stirrer is

set at 500 rpm for the conventional method. The ultrasonic method uses a 1000W power output and frequency of 20-36 kHz. The experiment shows that transesterification process through an ultrasonic method achieved 97.4% yield, much higher than the conventional method 93% yield. That is because the transesterification process through ultrasonic method boosted the speed for chemical reactions with the help of cavitation (Bahadur et al., 2015). In line with the previous research, Figure 4.6 shows the yield of *Reutealis trisperma* oil transesterification process as a function of time. As shown in the Figure 4.6, the ultrasonic bath stirrer method of 1 hour 30 minutes, 0.5 wt. % of potassium hydroxide and methanol-to-oil ratio 60%, gave the optimum yield of 95.29%. Increment in reaction time of the transesterification process for over 1 hour 30 minutes reduced biodiesel yield. Whereas in the conventional method, an increase in time of the transesterification process for over 1 hour 30 minutes increases biodiesel yield. This conventional process requires higher amount of methanol and longer reaction time, thus this method requires more energy to produce biodiesel of similar results to that of ultrasonic method. This ultrasonic process makes use of sound wave that cannot be heard by humans with frequencies ranging 20 kHz-100 kHz. These waves are capable of providing mechanical energy for stirring and provide activation energy to initiate transesterification reactions. The sound waves with specific frequencies are transmitted effectively via transducer to oil and alcohol. The wave is measured by the number of cavitation bubbles formed in the liquid. Furthermore, the emergence and disappearance of cavitation bubbles can negate the phase boundary in the 2-phase liquid system. The loss of the film layer between the two layers causes easy formation of emulsions, with droplet size of alcohol and oil in units of micrometers. The interface areas of alcohol and oil droplets are increased so that the transesterification reaction process can occur effectively. Finally, this ultrasonic process can increase the amount of product and yield, which is obtained at the end of the reaction (Budiman et al., 2014).

These results have been proven by Mootabadi et al. (2010) who conducted transesterification studies of palm oil using ultrasonic cavitation assistance with 20 kHz and metal oxide catalysts (CaO, SrO, and BaO) for 10-60 minutes reaction time. Their research found that at the optimum conditions and 60 minutes of reaction time can produce up to 95% biodiesel yield as compared to conventional stirring which takes 2-4 hours reaction time (Mootabadi et al., 2010). Furthermore, other study conducted by Chen YH et al. (2011) via an ultrasonic transesterification process uses Tung oil and mixed oil with a molar ratio of methanol to oil 6:1, 1 wt. % catalyst concentration, 25 kHz ultrasonic frequency and power 270 W at temperature 30°C. These results found that the ultrasonic transesterification method can produce up to 91.15% and 94.03% biodiesel yield at 30 min reaction time for Tung oil and mixed oil, respectively. In conclusion, biodiesel production using the ultrasonic transesterification method saves time reaction and effectively and conserves energy (Chen et al., 2011).

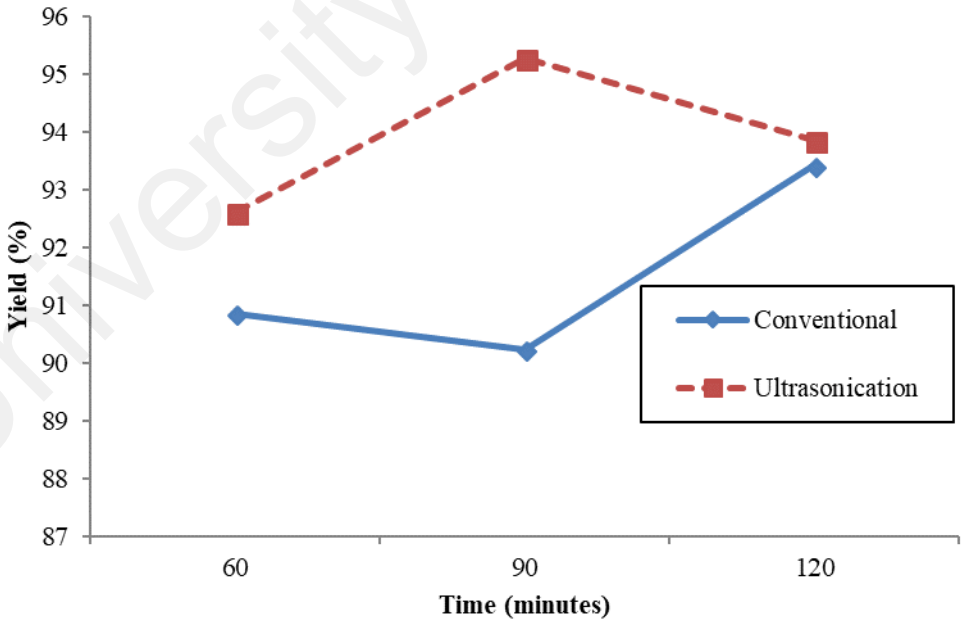


Figure 4.6: Effect of transesterification process on biodiesel yield of *Reutealis trisperma*

4.4.6. The summaries of conventional and ultrasonic method

The esterification and transesterification process through conventional and ultrasonic methods can be summarized in a brief outline of the comparison of these two methods. Ultrasonic method is more efficient in experiment process compared to conventional method. It can save reaction time and energy consumption to reduce the cost of production. In addition, from the experimental results, it is found that the yields from ultrasonic method are higher compared to conventional methods. These advantages will greatly assist the production of biodiesel if used for large-scale biodiesel production. The Table 4.4 below shows a general summary of the two methods used.

Table 4.4. Comparison between conventional and ultrasonic method for biodiesel production

Characteristic	**Conventional**	**Ultrasonic**
Reaction time	3 to 5 hours (long)	1 to 3 hours (short)
Catalyst required	Yes	Yes
Heat losses	High	Low
Process efficiency	Moderate	High
Advantages	Simple to operate and uses low energy source	Short reaction and high energy efficiency
Conversion yield	Moderate	High
Large scale production	Yes	Yes

4.5. Life cycle cost analysis and sensitivity analysis of *Reutealis trisperma*

4.5.1. Economic indicator

As mentioned in the previous chapter, the lifetime of the project has been set to 20 years, which includes the first year of construction and startup of the plant. It is assumed that the plant shall operate at 100% capacity throughout the duration of the project. Capital costs for the project are assumed to be paid through private investment and no loans are taken for the project; to make our calculations simpler, as no repayment on the loans is considered. The capital costs for the plant are calculated based on the required land area, equipment and instrumentations, as well as the cost for building

construction. The feedstock under consideration in this work is *Reutealis trisperma* oil, which shall be used for the production of biodiesel oil. To operate at maximum capacity, approximately 57 ktons of crude *Reutealis trisperma* oil is required to produce 50 ktons of biodiesel, assuming a biodiesel conversion efficiency (*CE*) of 98%. The selling price of biodiesel is taken to be $0.47/liter for the first ten years and $2.00/liter for the rest of the project lifetime.

4.5.2. Life cycle cost analysis and payback period

The data from Table 3.2 are used to calculate the life cycle cost and payback period for biodiesel plant using *Reutealis trisperma* oil in Malaysia. The results of the calculations are shown in Table 4.5 and Figure 4.7. The results of the analysis indicated that the total life cycle cost of the project is approximately $710 million, giving a unit cost of the biodiesel fuel of $0.696/litre of biodiesel. The unit price of $0.696/liter of biodiesel is lower than the $0.78/liter price calculated by Yusuf and Kamarudin for biodiesel from *Jatropha curcas* (Yusuf & Kamarudin, 2013), however, it is higher than $0.64/liter price calculated by Ong et al. for biodiesel from palm oil (Ong et al., 2012). It is also higher than the retail price of $0.58/liter for fossil diesel in Malaysia. Other studies have been reported by Lee et al. (2011) by conducting simulation and economic analysis on biodiesel production process using rapeseed oil and waste canola oil through supercritical methanol process. The analysis has been done for 40 ktons/year plant capacity. From the analysis found that the biodiesel cost $1.27/liter and $0.81/liter for rapeseed oil and waste canola oil, respectively (Lee et al., 2011). Where that cost was higher than biodiesel unit cost from *Reutealis trisperma* oil $0.696/liter.

The feedstock cost of crude *Reutealis trisperma* oil is the biggest contributors to the life cycle cost of the project; with a percentage of around 83% of the total life cycle cost or $0.5896 for every liter of biodiesel produced. This is followed by its operating costs;

with a percentage of around 17% of the total life cycle cost or $0.13 for every liter of biodiesel produced during the 20-year project lifetime. The sales of glycerol, by-product of the plant, contributed $16,927,840. This is equivalent to the plant clawing back $0.0169 for every liter of biodiesel produced. The time for the project to recoup its initial capital investment of $11,882,425 or its payback period is 4.34 years and thus, the payback period is less than one fourth of the lifetime of the project. These results indicated the economic feasibility of the project. The payback period is an effective tool to predict the time needed to return investment used in early stage of development of the project. This tool can be used by financial management to monitor recovery of project time.

Based on the results from Agricultural Research and Development, Ministry of Agriculture, in Indonesia, the seed production is estimated to reach 15-20 tons/ha or equivalent to 8-10 tons of oil/ha/year. *Reutealis trisperma* is also available in the Malay Peninsula area. The candidates have not completed a thorough study of how many estates are available today, but the land and climate criteria in Malaysia are the same as Indonesia. Thus, the opportunity to be grown in large quantities as an alternative energy supply and environmental rehabilitation in Malaysia is enormous. As Kalam M.A et al reported (2012), Malaysia has approximately 1.5 million ha of marginal land that can be used for plantation processing (Kalam et al., 2012). Currently the Malaysian Institute of Agricultural Research and Development (MARDI) is focusing on research for potential production of *Jatropha curcas* while the Department of Plant Sciences, Faculty of Agriculture, Universiti Putra Malaysia is discussing the commercial opportunities and barriers of biodiesel production from *Jatropha curcas*. It is very likely that the *Reutealis trisperma*, which also comes from non-edible oil, can be one of the feedstocks that are developed in large numbers.

Table 4.5: Summary of total production cost and payback period of biodiesel production plant

Indicator	Life cycle cost ($)	Unit cost ($/l of biodiesel)
Capital cost	11,882,425	0.0119
Operating cost	122,726,843	0.1227
Maintenance cost	2,916,585	0.0029
Feedstock cost	589,522,106	0.5896
Salvage value	260,841	0.0003
By product credit	16,927,840	0.0169
Total biodiesel cost	709,959,278	0.6966
Payback period (year)	-	4.34

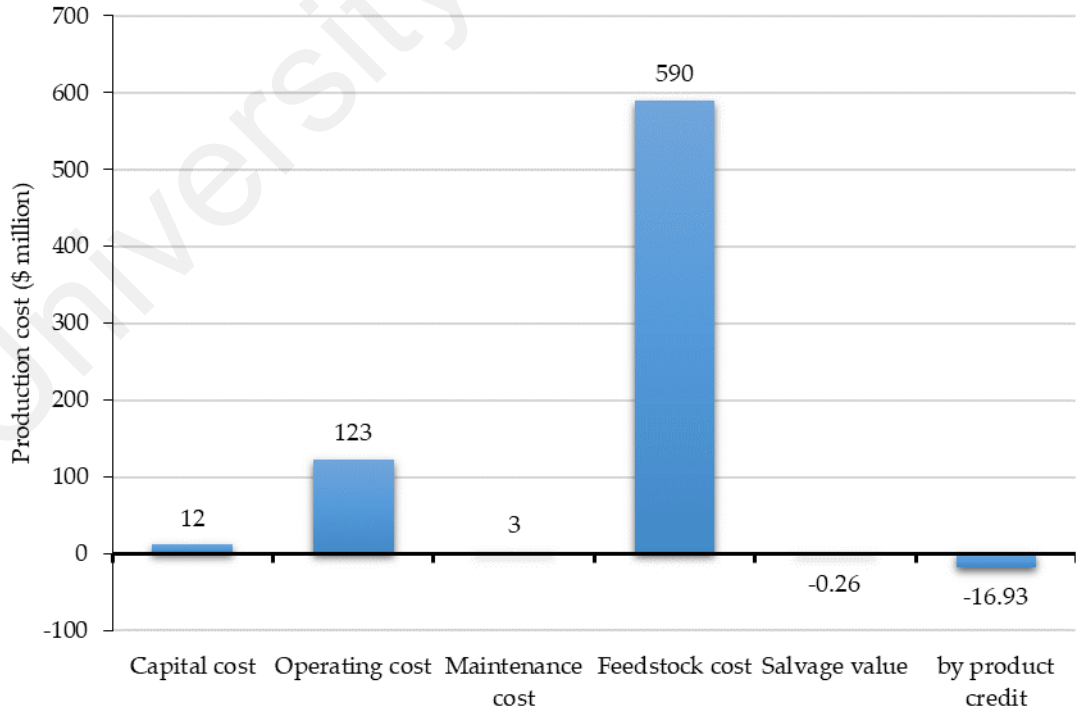


Figure 4.7: Distribution of *Reutealis trisperma* biodiesel production cost

4.5.3. Potential Fuel Saving

The sum of diesel fuel substitution is a function of the yearly diesel fuel consumption with a substitution ratio with biodiesel. The total biodiesel required for replacing the diesel fuel is estimated by the diesel fuel substitution multiplied by the biodiesel to diesel fuel substitution ratio. Since biodiesel and diesel fuels have some dissimilarity in heating value or calorific value, there are different amounts of biofuel required to replace fossil diesel fuel. The fossil diesel consumption and potential diesel replacement are tabulated in Table 4.6.

Table 4.6: Fossil diesel consumption and potential diesel replacement.

Year	Diesel Consumption		Diesel Replacement/Saving	
	(Million liters)	(Tons)	(Million liters)	(Tons)
2018	9,907	8,291,846	495	414,592
2019	10,187	8,526,812	509	425,341
2020	10,468	8,761,778	523	438,089
2021	10,749	8,996,743	537	449,837
2022	11,030	9,231,709	551	461,585
2023	11,310	9,466,675	566	473,334
2024	11,591	9,701,641	580	485,082
2025	11,872	9,936,607	594	496,830
2026	12,152	10,171,573	608	508,579
2027	12,433	10,406,539	622	520,327
2028	12,741	10,641,505	636	532,075
2029	12,995	10,876,471	650	543,824
2030	13,275	11,111,437	664	555,572
2031	13,556	11,346,403	678	567,320

Table 4.6: continued

Year	Diesel Consumption		Diesel Replacement/Saving	
	(Million liters)	(Tons)	(Million liters)	(Tons)
2032	13,837	11,581,369	692	579,068
2033	14,117	11,816,335	706	590,817
2034	14,398	12,051,301	720	602,565
2035	14,679	12,286,267	734	614,313
2036	14,960	12,521,233	748	626,062
2037	15,240	12,756,198	762	637,810

4.5.4. Sensitivity analysis

Sensitivity analysis is performed to investigate the effect of variations on some input parameters on the life cycle cost of the project. Five input variables of the model are chosen for the analysis; feedstock unit price (*FP*), operating rate (*OR*), initial capital cost (*CC*), interest rate/discount rate (*r*), and biodiesel conversion efficiency or oil conversion yield (*CE*). The feedstock cost (*FC*), operating cost (*OC*), and initial capital cost (*CC*) are the three dominant factors associated with the *LCC* as identified in Equation (1) and are demonstrated in Table 4.5 and Figure 4.7; with feedstock cost and operating cost determined by the feedstock unit price (*FP*) and operating rate (*OR*), respectively. As present value calculations are employed, the interest rate value (*r*) also influences the *LCC* of the project; to be expected with high interest rates that can reduce the LCC value of the project and vice versa. Finally, since the plant is assumed to produce at its maximum capacity of 50 ktons of biodiesel, the biodiesel conversion efficiency (*CE*) dictates the amount of feedstock that should be fed into the plant to produce the required output. Figure 4.8 below demonstrates the effect of varying the

five input variables on the *LCC* of the biodiesel project. The left side of the figure shows the possible values of the variables; "favorable", "assumed", and "unfavorable" values on the order of appearance. For instance, the "assumed" value of the feedstock price ($980/t) is the value used in the *LCC* calculations, giving a *LCC* value indicated by the mid-line on the figure. A reduction in the feedstock price to the "favorable" value ($680/t) lowers the *LCC* value to less than approximately $530 million when and its increase to "unfavorable" value of ($1280/t). The *LCC* value increases to approximately $890 million.

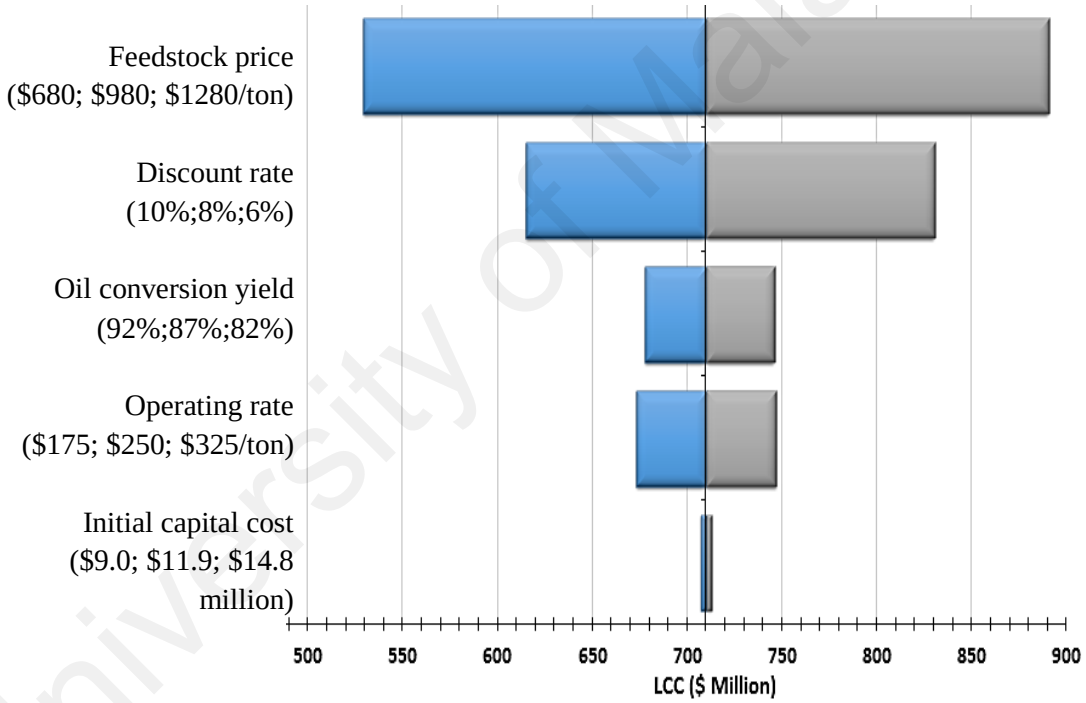


Figure 4.8: Sensitivity analysis of life cycle costs for *Reutealis trisperma* biodiesel plant production

It can be seen from the figure that variations in feedstock prices have the most impact on the life cycle cost of the project. This is as expected as the feedstock price was previously identified to be the most dominant cost associated with the *LCC*. From the

figure, a reduction in the price of *Reutealis trisperma* oil from $980/t to $680/t reduces the total life cycle cost from approximately $710 million to $529 million, while an increment in price to $1280/t gives a total life cycle cost of $890 million. This is followed by the interest rate/discount rate used in the calculation of *LCC*. An increase of the interest rate to 10% per annum results in a 13% reduction in total life cycle cost while a decrease to 6% per annum results in a 17.5% increase in the total life cycle cost. For the operating rate; which is defined as the operating cost per ton of biodiesel produced, decreasing the rate to $175/t reduces the total life cycle cost to $673 million or a reduction of 5% from the original *LCC*. Increasing the operating rate to $325/t increases the total life cycle cost to $746 million, in corresponding to a 5% increase. From the figure, the *LCC* value is least sensitive to variation in the Initial Capital Cost (*CC*) and is then followed by the biodiesel conversion efficiency (*CE*). The relationship between the market price of crude *Reutealis trisperma* oil prices and final biodiesel unit cost (*FBC*) is warranted and is shown in Figure 4.9. It can be seen that the final biodiesel unit cost (*FBC*) has a linear correlation with the price of the feedstock; an increase in the price of *Reutealis trisperma* oil by $0.1/kg results in an increase in the final biodiesel unit cost by $0.05/liter.

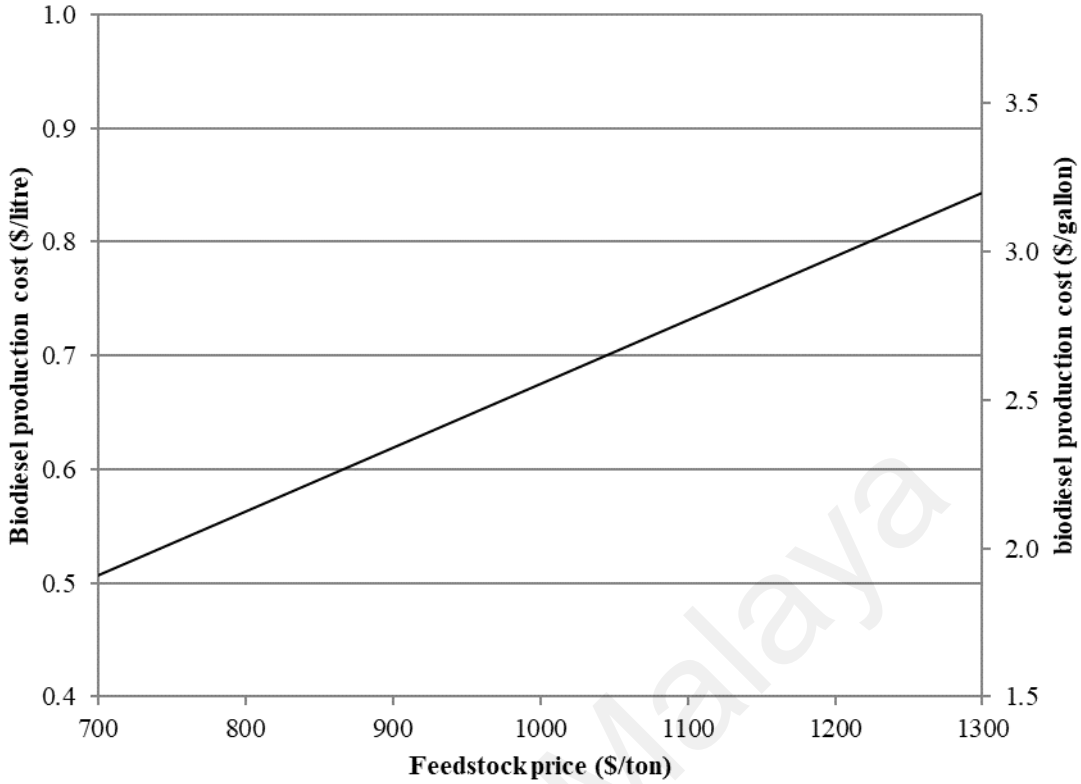


Figure 4.9: The impact of feedstock oil price on the biodiesel production cost

4.5.5. Biodiesel taxation and subsidy scenarios

Taxation and subsidy levels play important roles in encouraging the adoption of biodiesel as a replacement for fossil diesel, especially as biodiesel is currently less attractive when compared to fossil diesel economically. Imposing a high tax rate has the effect of increasing its selling price while giving a subsidy helps biodiesel to be more competitive in the market. Table 4.7 provides a comparison of the effect of different taxation and subsidy policies on the competitiveness of the biodiesel derived from *Reutealis trisperma*. These four scenarios; 1) total tax exemption, 2) a tax rate of 15%, 3) subsidy amounts of $0.10/liter and $0.18/liter on the biodiesel, are analyzed and compared with the price of fossil diesel which is currently at $0.58/liter (November 2017 - February 2018), the retail price of diesel fuel in Malaysia. It is noted that subsidy amounts of $0.10/liter and $0.18/liter are current subsidies given by the Malaysian government for petrol fuel and fossil diesel, respectively. The biodiesel to fossil diesel

substitution ratio is taken to be 1.07. This allows for a like-for-like comparison of biodiesel and fossil diesel on the basis of energy production, instead of on the basis of volume. At the current subsidy for fossil diesel of $0.18/liter, the price of the biodiesel is actually lower than the fossil diesel. In fact, the subsidy cost at anything above $0.12/liter makes biodiesel to have lower price than fossil diesel and hence, is more competitive. Of course, this is based on the assumptions previously made on the different costs associated with the production of biodiesel from *Reutealis trisperma* oil; importantly the feedstock cost of $980/t, the subsidy cost of fossil diesel at $0.18/liter, as well as the retail price of fossil diesel at $0.58/liter.

Table 4.7: Biodiesel taxation and subsidy level scenarios at current production cost

$/liter	**Biodiesel**				**Fossil Diesel**
	Total Tax Exemption	**15% Of Tax**	**Subsidy ($0.10/liter)**	**Subsidy ($0.18/liter)**	
Biodiesel Cost ($/liter)	0.697	0.697	0.697	0.697	-
Taxes/Subsidy ($/liter)	-	0.104	0.10	0.18	-
Total ($/liter)	0.697	0.801	0.597	0.517	0.581
Total Cost ($/liter diesel)	0.703	0.808	0.602	0.521	0.581

Naturally, the market prices of crude petroleum oil and *Reutealis trisperma* oil are important factors in determining whether biodiesel from *Reutealis trisperma* oil can actually compete with fossil diesel or subsidies are required to encourage the use of biodiesel. Figure 4.10 presents the breakeven price of *Reutealis trisperma* oil used in the production of biodiesel at different prices of crude petroleum oil. For a given price of crude petroleum oil, *Reutealis trisperma* oil prices above the line indicates that the subsidy is required for biodiesel to compete with fossil diesel, while any prices below it

indicates that no subsidy is required, and savings may be expected by substituting fossil diesel with biodiesel. As an example, for the price of crude petroleum oil at $100/barrel, any price above $1585/t (on the line) for the *Reutealis trisperma* oil would require a biodiesel subsidy so that biodiesel would be able to compete with fossil diesel. Any price below $1585/t would make biodiesel naturally attractive and savings may be expected by using biodiesel. The opposite is also true. For a given price of crude *Reutealis trisperma* oil (CRTO), the upper part of the line indicates that the subsidy for the CRTO biodiesel is required to encourage the use of biodiesel over fossil diesel. On the contrary, the lower part of the line is indicating that savings can potentially be obtained by substituting from fossil diesel to biodiesel. Figure 4.11 plots the final biodiesel unit cost (FBC) as a function of feedstock price (*FP*), with the fixed retail price of fossil diesel at $0.58/liter and fossil diesel subsidy of $0.18/liter. It can be seen that at feedstock prices below $0.8/kg, biodiesel can compete with fossil diesel, provided that biodiesel is tax exempted. At biodiesel subsidy levels of $0.10/liter and $0.18/liter, biodiesel remains competitive against fossil diesel provided that the feedstock prices do not exceed $1/kg and $1.19/kg, respectively. Feedstock prices over these values would see the price of biodiesel is higher than fossil diesel.

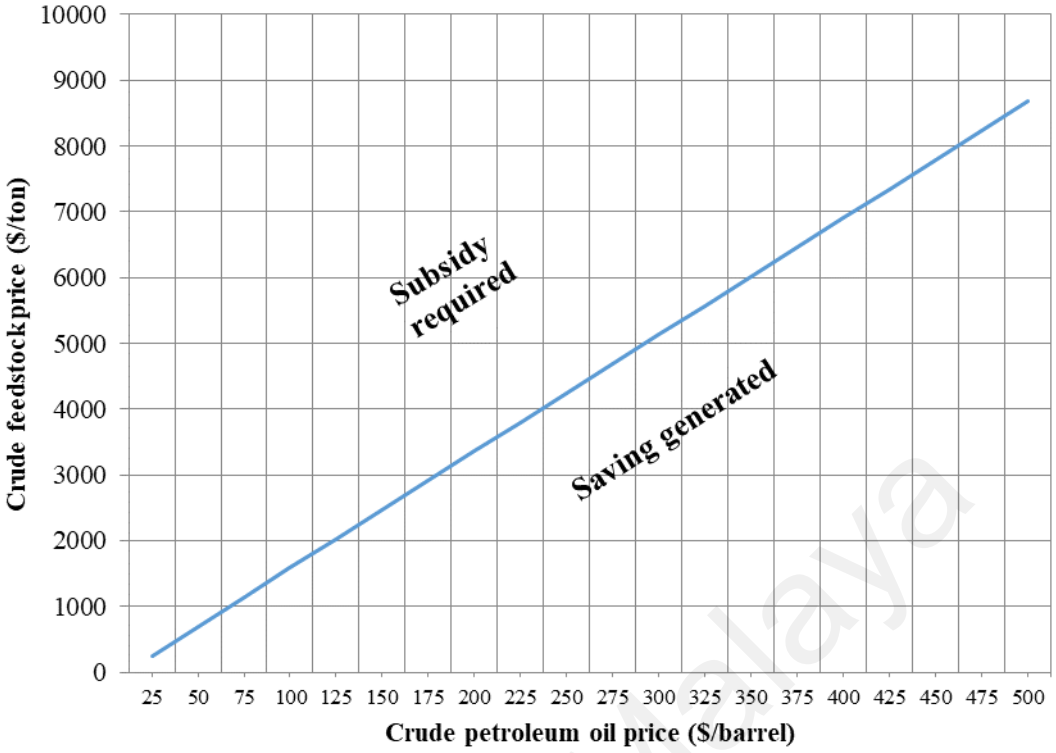


Figure 4.10: Breakeven price for biodiesel production at different petroleum and feedstock prices

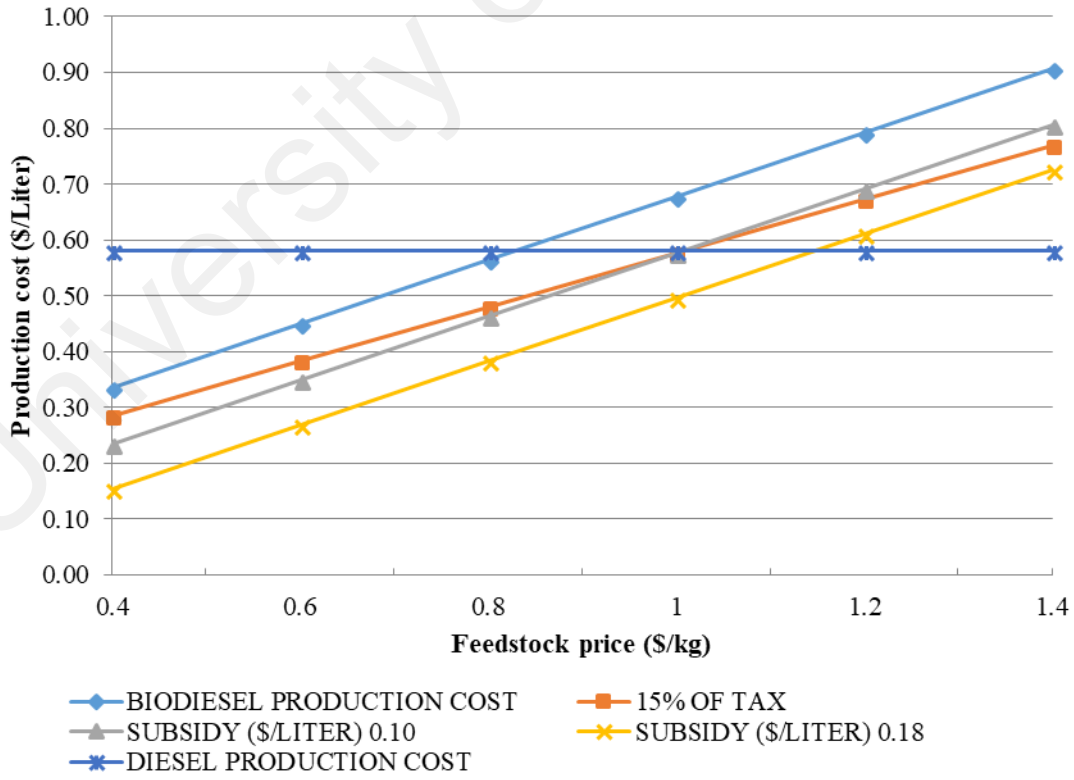


Figure 4.11: Taxation and subsidy scenarios of biodiesel production cost on feedstock price

4.5.6. Potential environmental impact

Analysis on the potential environmental impact of adopting biodiesel includes potential emission reduction that may be achieved by substituting fossil diesel with biodiesel. This may simply be represented by the total energy saved (TGS_i) from foregoing fossil diesel as well as the potential reduction in carbon emission (TCS_i) from the substitution. Also, estimation of the cropland required for the feedstocks (CLR_i) is important. The results from the analysis for different replacement rates but the fixed assumption on fossil diesel, are given in Table 4.8 below. An increase in the fossil diesel replacement rate causes an increment in the amount of biodiesel required to facilitate the biodiesel to fossil diesel substitution. This increase in the requirement for biodiesel necessitates more cropland to supply the increasing feedstock. Diesel replacement rates of 1%, 20% and 50% require 31 kHa, 626 kHa and 1564 kHa of cropland, respectively. Substituting fossil diesel with biodiesel obviously reduces fossil diesel consumption which translates into total energy saving from fossil diesel. Furthermore, as biodiesel is more environment-friendly than fossil diesel, in terms of carbon emission, the substitutions also translate into total carbon savings.

Table 4.8: The results, by changing the number of replacements for cropland required total energy saving and total carbon saving

Diesel Consumption	Diesel Replacement Rate	Diesel Replacement Rate	Biodiesel Needed	Cropland Required	Total Energy Saving (Diesel)	Total Carbon Saving
DC		DR	BC	CLR	TES	TCS
8,291,846 (TONS)	(%)	(TONS)	(TONS)	(HA)	(GJ)	(KG)
2018	1%	82,918	89,126	31,300	3,573,785	127,169
2019	2%	165,837	178,253	62,599	7,147,571	524,338
2020	3%	248,755	267,379	93,899	10,721,356	381,507
2021	4%	331,674	356,505	125,199	14,295,142	508,676
2022	5%	414,592	445,631	156,499	17,868,927	635,845
2023	6%	497,511	534,758	187,798	21,442,713	763,014
2024	7%	580,492	623,884	219,098	25,016,498	890,183
2025	8%	663,348	713,010	250,398	28,590,284	1,017,352
2026	9%	746,266	802,137	281,698	32,164,069	1,144,521
2027	10%	829,185	891,263	312,997	35,737,855	1,271,691
2028	15%	1,243,777	1,336,894	469,496	53,606,782	1,907,536
2029	20%	1,658,369	1,782,526	625,994	71,475,710	2,543,381
2030	25%	2,072,961	2,228,157	782,493	89,344,637	3,179,226
2031	30%	2,487,554	2,673,788	938,992	107,213,565	3,815,072
2032	35%	2,902,146	3,119,420	1,095,490	125,082,492	4,450,917
2033	40%	3,316,738	3,565,051	1,251,989	142,951,420	5,086,762
2034	45%	3,731,331	4,010,683	1,408,488	160,820,347	5,722,607
2035	50%	4,145,923	4,456,314	1,564,986	178,689,275	6,358,453

Figure 4.12 illustrates the total carbon emission from fossil diesel and biodiesel for different years having different diesel replacement rates. Although total carbon emissions from both fossil diesel and biodiesel increase with an increase in the diesel replacement rate, total carbon emissions from fossil diesel is clearly higher due to its higher carbon emission factor. As shown in Figure 4.12 the comparison of total carbon emitted by diesel and biodiesel. The Figure 4.12 shows that there is a difference in value of CO2 emissions between diesel fuel and biodiesel. The first year of plant based on calculations, total carbon emitter from diesel fuel is 1585 ktons while biodiesel fuel is 949 ktons. Furthermore, based on calculations, in the year 2037 total carbon emitter diesel fuel has reached 2438 ktons but total carbon emitter biodiesel will only be 1460 ktons. The difference between the carbon emissions from fossil diesel and carbon emissions from biodiesel, gives the total carbon saving (*TCS*) due to the diesel substitutions; from a more polluting fossil diesel to a more efficient biodiesel. From the Table 4.8, the diesel replacement rate of 1% results in total energy savings from diesel (*TGS*) of 3,573,785 MJ and total carbon saving (*TCS*) of 127,169 kg, and at the diesel replacement rate of 20%, total energy savings from diesel (*TGS*) and total carbon saving (*TCS*) are 71,575,710 MJ and 2,543,381 kg, respectively. Increasing the replacement rate has further been shown to further increase the *TGS* and *TCS* values. Meanwhile, the ecosystem carbon payback period may be estimated by dividing the difference between the carbon stock from converting the natural land into biodiesel feedstock cropland with the yearly carbon savings by utilizing biodiesel fuel, as given in Equation (3.30). A carbon payback period (*CPP*) value of 25 years is obtained.

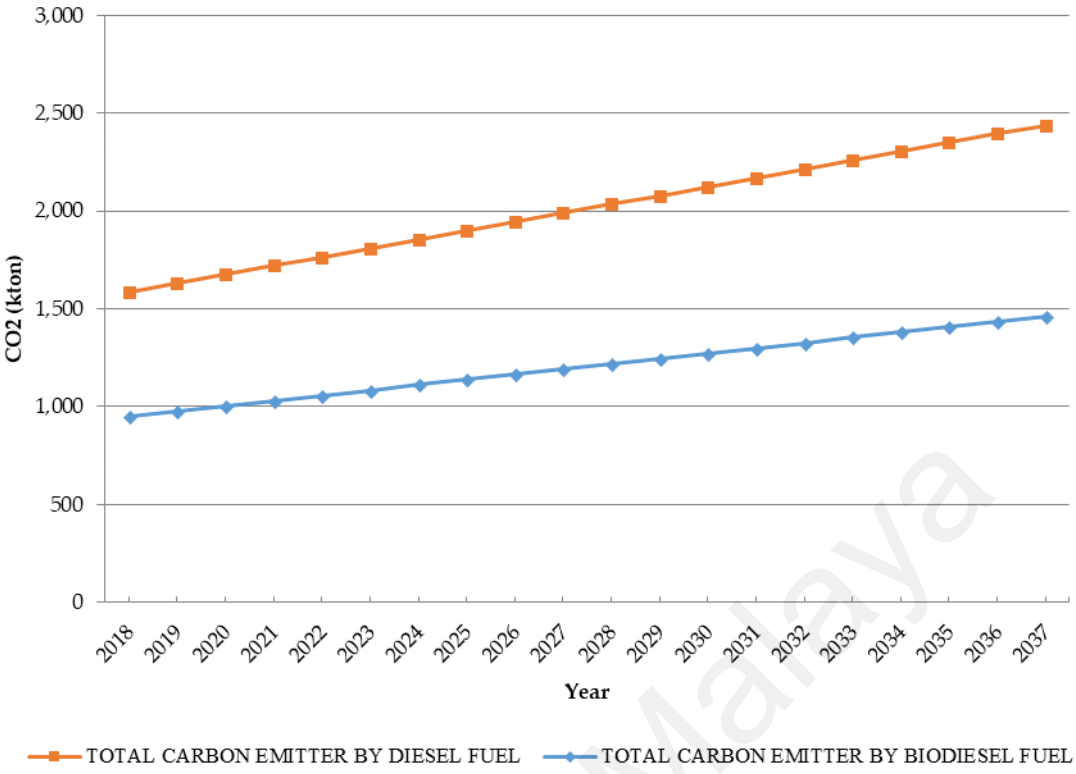


Figure 4.12: Comparison of total carbon emitted by diesel fuel and biodiesel

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The improvement of technology is quick accompanied by an increase of the number of vehicles in Malaysia and it will lead to higher fuel consumption and environmental emissions effect in the future. To resolve this problem, biodiesel from vegetable oil is an alternative fuel that is environment-friendly in order to reduce dependence on fossil fuels. This study focuses on the investigation of the feasibility of *Reutealis trisperma* oil as biodiesel fuel and techno-economic as well as sensitivity analysis of biodiesel production from *Reutealis trisperma* oil in Malaysia. The conclusions are summarized as follows:

1. The conclusions from the biodiesel production of crude *Reutealis trisperma* oil are to investigate the feasibility and characteristics of *Reutealis trisperma* biodiesel fuel has been analyzed in laboratory experiments. Two methods of transesterification are analyzed: conventional and ultrasonic bath stirrer method in biodiesel production from crude *Reutealis trisperma* oil. The effect on acid value, kinematic viscosity and yield versus time of reaction are discussed. The result showed that the optimum quality of biodiesel with the shortest time has been obtained by using the ultrasonic bath stirrer method for a total time of esterification and transesterification process of 2 hours 30 minutes. The yield is obtained up to 95.29%, acid value is 0.268 mg KOH/g and kinematic viscosity is 6.48 mm^2/s. Whereas, the conventional method takes up to five hours for the esterification and transesterification process to obtain similar results. The properties of *Reutealis trisperma* biodiesel are also tested. Most of the properties are in agreement with ASTM D6751 and EN 14214 standard except for kinematic viscosity. However, the viscosity can be reduced by blending this

biofuel with diesel fuel with suitable mixing ratio. Thus, the first and second objectives of investigating the feasibility and analyzing the characteristic properties of biodiesel fuel *Reutealis trisperma* are completed.

2. Finally, the techno-economic and sensitivity analyses of the *Reutealis trisperma* plant as a source of feedstocks for a biodiesel production plant in Malaysia for 20-year lifetime is conducted. Consequently, a model is developed to calculate the feasibility of the plant based on life cycle costs, payback period, etc., as well as its sensitivity to changing input variables. The present model is to develop a 50 ktons biodiesel production plant with an estimated lifetime of 20 years. The life cycle costs and payback period for the biodiesel plant from crude *Reutealis trisperma* oil are calculated to be approximately $710 million and 4.34 years, respectively. The total biodiesel unit cost is estimated to be $0.69/liter; which is competitive with fossil diesel that provided appropriate taxation and subsidy policies are in place. However, further studies on biodiesel production method, the cost of subsidize and other limiting factors to overcome them are necessary before a biodiesel production plant can be implemented in Malaysia.

5.2. Recommendations

The biodiesel production is growing very rapidly because biodiesel fuel has a good impact on the environment and sustainability. The study proposes several recommendations to improve the quality of biodiesel production, the optimal impact of fuel savings and the economic impacts in the application of biodiesel as a fuel. Recommendations are summarized as follows:

1. Biodiesel production should be further optimized and enhanced for higher quality and yield of biodiesel oil. The transesterification process through a two-stage process of high FFA vegetable oil can increase the cost and time efficiency of the production process. It is advisable to develop and conduct further research on biodiesel production by blending with diesel fuel or through different production methods such as heterogeneous catalysts to improve the efficiency and accelerate processes. Further research should also be done on more sophisticated methods (e.g. microwave-assisted) to reduce costs and turn it into more environment-friendly approach.
2. Biodiesel has been tested according to ASTM D6751 and EN 14214 standards to meet minimum criteria before engine testing on diesel engines. Here, the researches and studies of engine testing are recommended from biodiesel fuel and diesel mixtures in order to find engine performance, combustion and emissions from these biodiesel fuels.
3. Comprehensive life cycle study is needed to analyze energy balance, overall production cost from cultivation process, biodiesel feedstock harvest, raw material production process to biodiesel production cost and energy consumption as well as the combustion of biodiesel fuel. In addition, policies and standards on implementing biodiesel are the responsibility of policymakers that should be evaluated. Governments should take the initiative to direct the

policy into using biofuels. The most important factor to successfully implement biofuels is equalizing the purchasing power of society with the biofuel price. Therefore, in the future, the government is expected to be more proactive and to empower the use of biofuels in cooperation with the Malaysian Automotive Association, Malaysia Automotive Institute and Malaysia Energy Center for further biofuel development.

Finally, this research is expected to be a guide and a starting point for the application of biodiesel production from non-edible oil and its utilization as a viable fuel in Malaysia. It is hoped that this thesis can encourage more researchers and practitioners to be involved in this field in order to improve future suitability and further utilization of biofuels which will eventually preserve the environment.

References

(FOC), F. o. C. (2016). Reutealis trisperma. 2016, from http://www.efloras.org/florataxon.aspx?flora_id=2&taxon_id=220011492

(ISC), I. S. C. (2016). *Reutealis trisperma* (Philippine tung). 2016, from http://www.cabi.org/isc/datasheet/4125

(WAC), W. A. C. (2009). Calophyllum inophyllum. Retrieved 23 April, 2015, from http://www.worldagroforestry.org/treedb/AFTPDFS/Calophyllum_inophyllum.PDF

(WAC), W. A. C. (2010). Sterculia foetida. 2016, from http://www.worldagroforestry.org/treedb2/AFTPDFS/Sterculia_foetida.pdf

Aditiya, H. B., Sing, K. P., Hanif, M., & Mahlia, T. M. I. (2015). Effect of acid pretreatment on enzymatic hydrolysis in bioethanol production from rice straw. *International Journal of Technology, 6*(1), 3-10.

Agarwal, A. K. (2007). Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in Energy and Combustion Science, 33*(3), 233-271.

Agarwal, A. K., & Das, L. (2001). Biodiesel development and characterization for use as a fuel in compression ignition engines. *Transactions-American Society of Mechanical Egineers Journal of Egineering for Gas Turbines and Power, 123*(2), 440-447.

Agarwal, A. K., & Dhar, A. (2009). Performance, emission and combustion characteristics of Jatropha oil blends in a direct injection CI engine: SAE Technical Paper.

Agarwal, A. K., & Dhar, A. (2013). Experimental investigations of performance, emission and combustion characteristics of Karanja oil blends fuelled DICI engine. *Renew Energ, 52*, 283-291.

Agarwal, A. K., Dhar, A., Gupta, J. G., Kim, W. I., Choi, K., Lee, C. S., et al. (2015). Effect of fuel injection pressure and injection timing of Karanja biodiesel blends on fuel spray, engine performance, emissions and combustion characteristics. *Energ Convers Manage, 91*, 302-314.

Ahmad, A. L., Yasin, N.H.M., Derek, C. J. C., Lim, J. K. (2011). Microalgae as a sustainable energy source for biodiesel production: A review. *Renewable and Sustainable Energy Reviews, 15*(1), 584-593.

Ahmad, J., Yusup, S., Bokhari, A., & Kamil, R. N. M. (2014). Study of fuel properties of rubber seed oil based biodiesel. *Energy Conversion Management, 78*(0), 266-275.

Akbar, E., Yaakob, Z., Kamarudin, S. K., Ismail, M., & Salimon, J. (2009). Characteristic and composition of Jatropha curcas oil seed from Malaysia and its potential as biodiesel feedstock feedstock. *European journal of scientific research, 29*(3), 396-403.

Al-Widyan, M. I., & Al-Shyoukh, A. O. (2002). Experimental evaluation of the transesterification of waste palm oil into biodiesel. *Bioresource Technol, 85*(3), 253-256.

Alamu, O. J., Waheed, M. A., & Jekayinfa, S. O. (2007). Biodiesel production from Nigerian palm kernel oil: effect of KOH concentration on yield. *Energy for Sustainable Development, 11*(3), 77-82.

Ali, E. N., & Tay, C. I. (2013). Characterization of biodiesel produced from palm oil via base catalyzed transesterification. *Procedia Engineering, 53*, 7-12.

Alptekin, E., & Canakci, M. (2008). Determination of the density and the viscosities of biodiesel–diesel fuel blends. *Renewable Energy, 33*(12), 2623-2630.

Alptekin, E., Canakci, M., & Sanli, H. (2014). Biodiesel production from vegetable oil and waste animal fats in a pilot plant. *Waste Management, 34*(11), 2146-2154.

Altun, Ş., & Lapuerta, M. (2014). Properties and emission indicators of biodiesel fuels obtained from waste oils from the Turkish industry. *Fuel, 128*, 288-295.

Ashraful, A., Masjuki, H., Kalam, M., Fattah, I. R., Imtenan, S., Shahir, S., et al. (2014). Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: a review. *Energy Conversion Management, 80*, 202-228.

Atabani, A., Mahlia, T., Badruddin, I. A., Masjuki, H., Chong, W., & Lee, K. T. (2013a). Investigation of physical and chemical properties of potential edible and non-edible feedstocks for biodiesel production, a comparative analysis. *Renewable Sustainable Energy Reviews, 21*, 749-755.

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

Atabani, A., Silitonga, A., Ong, H., Mahlia, T., Masjuki, H., Badruddin, I. A., et al. (2013c). Non-edible vegetable oils: a critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. *Renew Sust Energ Rev, 18*, 211-245.

Atabani, A. E., Silitonga, A. S., Badruddin, I. A., Mahlia, T., Masjuki, H., & Mekhilef, S. (2012). A comprehensive review on biodiesel as an alternative energy resource and its characteristics. *Renewable Sustainable Energy Reviews, 16*(4), 2070-2093.

Atadashi, I., Aroua, M., Aziz, A. A., & Sulaiman, N. (2013). The effects of catalysts in biodiesel production: A review. *Journal of industrial and engineering chemistry, 19*(1), 14-26.

Aunillah, A., & Pranowo, D. (2012). Karakteristik biodiesel kemiri sunan [Reutealis trisperma (Blanco) Airy Shaw] menggunakan proses transesterifikasi dua tahap. *Jurnal Tanaman Industri dan Penyegar, 3*(3), 193-200.

Aydin, C. (2007). Some engineering properties of peanut and kernel. *J Food Eng, 79*(3), 810-816.

Ayodele, O. O., & Dawodu, F. A. (2014). Production of biodiesel from Calophyllum inophyllum oil using a cellulose-derived catalyst. *Biomass and Bioenergy, 70*, 239-248.

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

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

Babajide, O., Petrik, L., Amigun, B., & Ameer, F. (2010). Low-cost feedstock conversion to biodiesel via ultrasound technology. *Energies, 3*(10), 1691-1703.

Bahadur, S., Goyal, P., Sudhakar, K., & Prakash Bijarniya, J. (2015). A comparative study of ultrasonic and conventional methods of biodiesel production from mahua oil. *Biofuels, 6*(1-2), 107-113.

Baiju, B., Naik, M., & Das, L. (2009). A comparative evaluation of compression ignition engine characteristics using methyl and ethyl esters of Karanja oil. *Renewable Energy, 34*(6), 1616-1621.

Balat, M. (2011). Potential alternatives to edible oils for biodiesel production–A review of current work. *Energy Conversion and Management, 52*(2), 1479-1492.

Balat, M., & Balat, H. (2010). Progress in biodiesel processing. *Appl Energ, 87*(6), 1815-1835.

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

Bindhu, C., Reddy, J., Rao, B., Ravinder, T., Chakrabarti, P., Karuna, M., et al. (2012). Preparation and evaluation of biodiesel from Sterculia foetida seed oil. *Journal of the American Oil Chemists' Society, 89*(5), 891-896.

Birla, A., Singh, B., Upadhyay, S., & Sharma, Y. (2012). Kinetics studies of synthesis of biodiesel from waste frying oil using a heterogeneous catalyst derived from snail shell. *Bioresource Technology, 106*, 95-100.

Boehman, A. L. (2005). Biodiesel production and processing. *Fuel Processing Technology, 86*(10), 1057-1058.

Boog, J. H. F., Silveira, E. L. C., De Caland, L. B., & Tubino, M. (2011). Determining the residual alcohol in biodiesel through its flash point. *Fuel, 90*(2), 905-907.

BPI. (2012). CEIBA PENTANDRA (Linn.) Gaertn. Buboi. Retrieved 14 March, 2015, from http://www.bpi.da.gov.ph/bpioldsite1/medicinalplant_b.php

Brennan, L., & Owende, P. (2010). Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews, 14*(2), 557-577.

Budiman, A., Kusumaningtyas, R., Pradana, Y., & Lestari, N. (2014). Biodiesel: Bahan Baku, Proses, dan Teknologi. *Yogyakarta: Gajah Mada University Press dan Anggota IKAPI*.

Can, Ö., Öztürk, E., Solmaz, H., Aksoy, F., Çinar, C., & Yücesu, H. S. (2016). Combined effects of soybean biodiesel fuel addition and EGR application on the combustion and exhaust emissions in a diesel engine. *Applied Thermal Engineering, 95*, 115-124.

Canakci, M., & Sanli, H. (2008). Biodiesel production from various feedstocks and their effects on the fuel properties. *J Ind Microbiol Biot, 35*(5), 431-441.

Candeia, R., Silva, M., Carvalho Filho, J., Brasilino, M., Bicudo, T., Santos, I., et al. (2009). Influence of soybean biodiesel content on basic properties of biodiesel–diesel blends. *Fuel, 88*(4), 738-743.

Chavan, S., Kumbhar, R., & Deshmukh, R. (2013). Callophyllum Inophyllum Linn ("honne") Oil, A source for Biodiesel Production. *Research Journal of Chemical Sciences, 2231*, 606X.

Chen, C.-R., Cheng, Y.-J., Ching, Y.-C., Hsiang, D., & Chang, C.-M. J. (2012). Green production of energetic Jatropha oil from de-shelled Jatropha curcas L. seeds using supercritical carbon dioxide extraction. *J Supercrit Fluid, 66*, 137-143.

Chen, Y.-H., Chang, C.-C., Chang, M.-C., & Chang, C.-Y. (2011). Biodiesel production from Tung oil and blended oil via ultrasonic transesterification process. *Journal of the Taiwan Institute of Chemical Engineers, 42*(4), 640-644.

Choedkiatsakul, I., Ngaosuwan, K., Cravotto, G., & Assabumrungrat, S. (2014). Biodiesel production from palm oil using combined mechanical stirred and ultrasonic reactor. *Ultrasonics Sonochemistry, 21*(4), 1585-1591.

Corporation, T. p. (2016). Reutealis trisperma from http://www.discoverlife.org/mp/20m?map=Reutealis+trisperma

Corseuil, H. X., Monier, A. L., Gomes, A. P., Chiaranda, H. S., do Rosario, M., & Alvarez, P. J. (2011). Biodegradation of soybean and castor oil biodiesel: implications on the natural attenuation of monoaromatic hydrocarbons in groundwater. *Groundwater Monitoring & Remediation, 31*(3), 111-118.

Davis, J., Dean, L., Faircloth, W., & Sanders, T. (2008). Physical and chemical characterizations of normal and high-oleic oils from nine commercial cultivars of peanut. *J Am Oil Chem Soc, 85*(3), 235-243.

Davis, J., Geller, D., Faircloth, W., & Sanders, T. (2009). Comparisons of biodiesel produced from unrefined oils of different peanut cultivars. *J Am Oil Chem Soc, 86*(4), 353-361.

de La Salles, K. T. S., Meneghetti, S. M. P., de La Salles, W.F., Meneghetti, M. R., dos Santos, I. C. F.,da Silva, J. P. V.,de Carvalho, S. H. V.,Soletti, J. I. (2010). Characterization of Syagrus coronata (Mart.) Becc. oil and properties of methyl esters for use as biodiesel. *Industrial Crops and Products, 32*(3), 518-521.

de Sousa, L. S., de Moura, C. V. R., de Oliveira, J. E., & de Moura, E. M. (2014). Use of natural antioxidants in soybean biodiesel. *Fuel, 134*, 420-428.

Dehkordi, A. M., & Ghasemi, M. (2012). Transesterification of waste cooking oil to biodiesel using Ca and Zr mixed oxides as heterogeneous base catalysts. *Fuel Processing Technology, 97*, 45-51.

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

Demirbas, A. (2009a). Biofuels: green energy and technology: Springer, Londres.

Demirbas, A. (2009b). Progress and recent trends in biodiesel fuels. *Energy Conversion and Management, 50*, 14-34.

Deng, X., Fang, Z., & Liu, Y.-h. (2010). Ultrasonic transesterification of Jatrophacurcas L. oil to biodiesel by a two-step process. *Energy Conversion and Management, 51*(12), 2802-2807.

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

Dhar, A., & Agarwal, A. K. (2013). Effect of multiple injections on particulate size-number distributions in a common rail direct injection engine fueled with Karanja biodiesel blends: SAE Technical Paper.

Dhar, A., & Agarwal, A. K. (2015a). Effect of Karanja biodiesel blends on particulate emissions from a transportation engine. *Fuel, 141*, 154-163.

Dhar, A., & Agarwal, A. K. (2015b). Experimental investigations of the effect of pilot injection on performance, emissions and combustion characteristics of Karanja biodiesel fuelled CRDI engine. *Energy Conversion and Management, 93*, 357-366.

Dharma, S., Masjuki, H., Ong, H. C., Sebayang, A., Silitonga, A., Kusumo, F., et al. (2016). Optimization of biodiesel production process for mixed Jatropha curcas–Ceiba pentandra biodiesel using response surface methodology. *Energy Conversion and Management, 115*, 178-190.

Dizge, N., & Keskinler, B. (2008). Enzymatic production of biodiesel from canola oil using immobilized lipase. *Biomass Bioenerg, 32*(12), 1274-1278.

Dwivedi, G., & Sharma, M. (2014). Impact of cold flow properties of biodiesel on engine performance. *Renew Sust Energ Rev, 31*, 650-656.

Dwivedi, G., & Sharma, M. P. (2015). Investigation and improvement in cold flow properties of Pongamia biodiesel. *Waste and Biomass Valorization, 6*(1), 73-79.

E., A. R., Mircea, V., M., B. A., A., K. J., & J., B. C. (2007). Transesterification of Fish Oil to Produce Fatty Acid Ethyl Esters Using Ultrasonic Energy. *Journal of the American Oil Chemists' Society, 84*(11), 1045-1052.

Fasina, O. (2008). Physical properties of peanut hull pellets. *Bioresource Technol, 99*(5), 1259-1266.

Fernández, C. M., Fiori, L., Ramos, M. J., Pérez, Á., & Rodríguez, J. F. (2015). Supercritical extraction and fractionation of Jatropha curcas L. oil for biodiesel production. *The Journal of Supercritical Fluids, 97*, 100-106.

Gandure, J., Ketlogetswe, C., & Temu, A. (2014). Fuel properties of biodiesel produced from selected plant kernel oils indigenous to Botswana: A comparative analysis. *Renew Energ, 68*, 414-420.

Georgogianni, K. G., Kontominas, M. G., Pomonis, P. J., Avlonitis, D., & Gergis, V. (2008). Conventional and in situ transesterification of sunflower seed oil for the production of biodiesel. *Fuel Processing Technology, 89*(5), 503-509.

Gole, V. L., & Gogate, P. R. (2013). Intensification of synthesis of biodiesel from non-edible oil using sequential combination of microwave and ultrasound. *Fuel Processing Technology, 106*, 62-69.

Gülüm, M., & Bilgin, A. (2015). Density, flash point and heating value variations of corn oil biodiesel–diesel fuel blends. *Fuel Processing Technology, 134*, 456-464.

Guo, F., Fang, Z., Tian, X.-F., Long, Y.-D., & Jiang, L.-Q. (2013). "One-step production of biodiesel from Jatropha oil with high-acid value in ionic liquids"[Bioresour. Technol. 102 (11)(2011)]. *Bioresource Technology, 140*, 447-450.

Haas, M. J., McAloon, A. J., Yee, W. C., & Foglia, T. A. (2006). A process model to estimate biodiesel production costs. *Bioresource Technology, 97*(4), 671-678.

Hanh, H. D., Dong, N. T., Starvarache, C., Okitsu, K., Maeda, Y., & Nishimura, R. (2008). Methanolysis of triolein by low frequency ultrasonic irradiation. *Energy Conversion and Management, 49*(2), 276-280.

Hazar, H., Ozturk, U., & Gul, H. (2016). Characterization and effect of using peanut seed oil methyl Ester as a fuel in a low heat rejection diesel engine. *Energy & Fuels, 30*(10), 8425-8431.

He, B., Van Gerpen, J., & Thompson, J. (2009). Sulfur content in selected oils and fats and their corresponding methyl esters. *Applied engineering in agriculture*, *25*(2), 223.

Hebbal, O. D., Reddy, K., Vijayakumar Rajagopal, K. (2006). Performance characteristics of a diesel engine with deccan hemp oi. *Fuel*, *85*(14-15), 2187-2194.

Hendra, D. (2014). Pembuatan biodiesel dari biji kemiri sunan. *Jurnal Penelitian Hasil Hutan*, *32*(1), 37-45.

Holilah, H., Prasetyoko, D., Oetami, T. P., Santosa, E. B., Zein, Y. M., Bahruji, H., et al. (2015). The potential of Reutealis trisperma seed as a new non-edible source for biodiesel production. *Biomass Conversion and Biorefinery*, *5*(4), 347-353.

Hosamani, K. M., Hiremath, V. B., Keri, R. S. (2009). Renewable energy sources from Michelia champaca and Garcinia indica seed oils: A rich source of oil. *Biomass and Bioenergy*, *33*(2), 267-270.

Huerga, I. R., Zanuttini, M. S., Gross, M. S., & Querini, C. A. (2014). Biodiesel production from Jatropha curcas: Integrated process optimization. *Energy Conversion and Management*, *80*, 1-9.

Hürdoğan, E. (2016). Thermodynamic analysis of a diesel engine fueled with diesel and peanut biodiesel. *Environmental Progress & Sustainable Energy*, *35*(3), 891-897.

Husnawan, M., Masjuki, H. H., & Mahlia, T. M. I. (2011). The interest of combining two additives with palm olein as selected lubricant components. *Industrial Lubrication and Tribology*, *63*(2-3), 203-209.

Illman, A., Scragg, A., & Shales, S. (2000). Increase in Chlorella strains calorific values when grown in low nitrogen medium. *Enzyme and microbial technology*, *27*(8), 631-635.

Issariyakul, T., Kulkarni, M. G., Dalai, A. K., & Bakhshi, N. N. (2007). Production of biodiesel from waste fryer grease using mixed methanol/ethanol system. *Fuel Process Technol*, *88*(5), 429-436.

IUCN. (2014). Reutealis trisperma. 2016, from http://www.iucnredlist.org/details/33898/0

Jøker, D., & Salazar, R. (2000). Ceiba pentandra. *Seed Leaflet*(22).

Kalam, M. A., Ahamed, J. U., & Masjuki, H. H. (2012). Land availability of Jatropha production in Malaysia. *Renewable and Sustainable Energy Reviews*, *16*(6), 3999-4007.

Kamath, H. V., Regupathi, I., & Saidutta, M. (2011). Optimization of two step karanja biodiesel synthesis under microwave irradiation. *Fuel Processing Technology*, *92*(1), 100-105.

Kansedo, J., Lee, K. T., & Bhatia, S. (2009). Cerbera odollam (sea mango) oil as a promising non-edible feedstock for biodiesel production. *Fuel, 88*(6), 1148-1150.

Kansedo, J., Lee, K.T., Bhatia, S. (2009). Cerbera odollam (sea mango) oil as a promising non-edible feedstock for biodiesel production. *Fuel, 88*(6), 1148-1150.

Karak, N. (2012). 3 - Vegetable oils and their derivatives. In N. Karak (Ed.), *Vegetable Oil-Based Polymers* (pp. 54-95): Woodhead Publishing.

Knothe, G. C., Steven C. Evangelista, Roque L. (2009). Cuphea Oil as Source of Biodiesel with Improved Fuel Properties Caused by High Content of Methyl Decanoate. *Energy & Fuels, 23*(3), 1743-1747.

Kreivaitis, R., Gumbytė, M., Kazancev, K., Padgurskas, J., & Makarevičienė, V. (2013). A comparison of pure and natural antioxidant modified rapeseed oil storage properties. *Ind Crop Prod, 43*, 511-516.

Kumar, D., Kumar, G., Poonam, & Singh, C. P. (2010). Fast, easy ethanolysis of coconut oil for biodiesel production assisted by ultrasonication. *Ultrasonics Sonochemistry, 17*(3), 555-559.

Kumar, K. R., Chandrika, K., Prasanna, K., & Gowda, B. (2015). Biodiesel production and characterization from non-edible oil tree species Aleurites trisperma Blanco. *Biomass Conversion and Biorefinery, 5*(3), 287-294.

Kwanchareon, P., Luengnaruemitchai, A., & Jai-In, S. (2007). Solubility of a diesel–biodiesel–ethanol blend, its fuel properties, and its emission characteristics from diesel engine. *Fuel, 86*(7–8), 1053-1061.

Lang, X., Dalai, A. K., Bakhshi, N. N., Reaney, M. J., & Hertz, P. (2001). Preparation and characterization of bio-diesels from various bio-oils. *Bioresource Technol, 80*(1), 53-62.

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

Lee, S., Posarac, D., & Ellis, N. (2011). Process simulation and economic analysis of biodiesel production processes using fresh and waste vegetable oil and supercritical methanol. *Chemical Engineering Research and Design, 89*(12), 2626-2642.

Lertsathapornsuk, V., Pairintra, R., Aryusuk, K., & Krisnangkura, K. (2008). Microwave assisted in continuous biodiesel production from waste frying palm oil and its performance in a 100 kW diesel generator. *Fuel Process Technol, 89*(12), 1330-1336.

Leung, D. Y., Wu, X., & Leung, M. (2010). A review on biodiesel production using catalyzed transesterification. *Applied Energy, 87*(4), 1083-1095.

Li, E., Xu, Z. P., & Rudolph, V. (2009). MgCoAl–LDH derived heterogeneous catalysts for the ethanol transesterification of canola oil to biodiesel. *Appl Catal B-Environ, 88*(1), 42-49.

Liu, C., Lv, P., Yuan, Z., Yan, F., & Luo, W. (2010). The nanometer magnetic solid base catalyst for production of biodiesel. *Renewable Energy, 35*(7), 1531-1536.

Liu, Y., Xin, H.l., Yan, Y.J. (2009). Physicochemical properties of stillingia oil: Feasibility for biodiesel production by enzyme transesterification. *Industrial Crops and Products, 30*(3), 431-436.

Lopez, G. P., & Laan, T. (2008). BIOFUELS - AT WHAT COST ?.Government support for biodiesel in Malaysia.

Lozada, I., Islas, J., & Grande, G. (2010). Environmental and economic feasibility of palm oil biodiesel in the Mexican transportation sector. *Renewable and Sustainable Energy Reviews, 14*(1), 486-492.

Luu, P. D., Truong, H. T., Van Luu, B., Pham, L. N., Imamura, K., Takenaka, N., et al. (2014). Production of biodiesel from Vietnamese Jatropha curcas oil by a co-solvent method. *Bioresource Technol, 173*, 309-316.

Maghami, M., Sadrameli, S., & Ghobadian, B. (2015). Production of biodiesel from fishmeal plant waste oil using ultrasonic and conventional methods. *Applied Thermal Engineering, 75*, 575-579.

Mahlia, T., Razak, H. A., & Nursahida, M. (2011). Life cycle cost analysis and payback period of lighting retrofit at the University of Malaya. *Renewable and Sustainable Energy Reviews, 15*(2), 1125-1132.

Malça, J., Coelho, A., & Freire, F. (2014). Environmental life-cycle assessment of rapeseed-based biodiesel: Alternative cultivation systems and locations. *Appl Energ, 114*, 837-844.

Marchetti, J., & Errazu, A. (2008). Technoeconomic study of supercritical biodiesel production plant. *Energy Conversion and Management, 49*(8), 2160-2164.

Masjuki, H. (2010). Biofuel engine: a new challenge. *Malaysia: University of Malaya*.

Mata, T. M., Martins, A.A., Caetano, N.S.,. (2010). Microalgae for biodiesel production and other applications: A review. *Renewable and Sustainable Energy Reviews, 14*(1), 217–232.

Math, M. C., Kumar, S. P., Chetty, S. V. (2010). Technologies for biodiesel production from used cooking oil -- A review. *Energy for Sustainable Development, 14*(4), 339-345.

Mejía, J., Salgado, N., & Orrego, C. (2013). Effect of blends of Diesel and Palm-Castor biodiesels on viscosity, cloud point and flash point. *Industrial Crops and Products, 43*, 791-797.

Mofijur, M., Masjuki, H., Kalam, M., Atabani, A., Shahabuddin, M., Palash, S., et al. (2013a). Effect of biodiesel from various feedstocks on combustion characteristics, engine durability and materials compatibility: A review. *Renewable Sustainable Energy Reviews, 28*, 441-455.

Mofijur, M., Masjuki, H. H., Kalam, M. A., Atabani, A. E., Shahabuddin, M., Palash, S. M., et al. (2013b). Effect of biodiesel from various feedstocks on combustion characteristics, engine durability and materials compatibility: A review. *Renewable and Sustainable Energy Reviews, 28*(0), 441-455.

Mootabadi, H., Salamatinia, B., Bhatia, S., & Abdullah, A. Z. (2010). Ultrasonic-assisted biodiesel production process from palm oil using alkaline earth metal oxides as the heterogeneous catalysts. *Fuel, 89*(8), 1818-1825.

Moser, B. R. (2012). Preparation of fatty acid methyl esters from hazelnut, high-oleic peanut and walnut oils and evaluation as biodiesel. *Fuel, 92*(1), 231-238.

Moser, B. R. (2014). Impact of fatty ester composition on low temperature properties of biodiesel–petroleum diesel blends. *Fuel, 115*(0), 500-506.

Naik, S. N., Goud, V. V., Rout, P. K., & Dalai, A. K. (2010). Production of first and second generation biofuels: a comprehensive review. *Renewable and Sustainable Energy Reviews, 14*(2), 578-597.

Nanthagopal, K., Ashok, B., & Raj, R. T. K. (2016). Influence of fuel injection pressures on Calophyllum inophyllum methyl ester fuelled direct injection diesel engine. *Energy Conversion and Management, 116*, 165-173.

Nurjanah, S., Lestari, D. S., Widyasanti, A., & Zain, S. (2015). The Effect of NaOH Concentration and Length of Transesterification Time on Characteristic of FAME from Reutealis trisperma (Kemiri Sunan). *International Journal on Advanced Science, Engineering and Information Technology, 5*(1), 52-56.

Ong, H., Mahlia, T., Masjuki, H., & Honnery, D. (2012). Life cycle cost and sensitivity analysis of palm biodiesel production. *Fuel, 98*, 131-139.

Ong, H., Mahlia, T., Masjuki, H., & Norhasyima, R. (2011a). Comparison of palm oil, Jatropha curcas and Calophyllum inophyllum for biodiesel: a review. *Renewable and Sustainable Energy Reviews, 15*(8), 3501-3515.

Ong, H. C. (2012). *Techno-economic analysis of biodiesel production from palm, Jatropha curcas and Calophyllum inophyllum for road transport in Malaysia/Ong Hwai Chyuan.* University of Malaya.

Ong, H. C., Mahlia, T. M. I., Masjuki, H. H., & Norhasyima, R. S. (2011b). Comparison of palm oil, Jatropha curcas and Calophyllum inophyllum for biodiesel: A review. *Renewable and Sustainable Energy Reviews, 15*(8), 3501-3515.

Ong, H. C., Masjuki, H., Mahlia, T., Silitonga, A., Chong, W., & Leong, K. (2014a). Optimization of biodiesel production and engine performance from high free

fatty acid Calophyllum inophyllum oil in CI diesel engine. *Energy Conversion and Management, 81*, 30-40.

Ong, H. C., Masjuki, H. H., Mahlia, T. M. I., Silitonga, A. S., Chong, W. T., & Yusaf, T. (2014b). Engine performance and emissions using Jatropha curcas, Ceiba pentandra and Calophyllum inophyllum biodiesel in a CI diesel engine. *Energy, 69*, 427-445.

Ong, H. C., Silitonga, A. S., Masjuki, H. H., Mahlia, T. M. I., Chong, W. T., & Boosroh, M. H. (2013a). Production and comparative fuel properties of biodiesel from non-edible oils: Jatropha curcas, Sterculia foetida and Ceiba pentandra. *Energy Conversion and Management, 73*(0), 245-255.

Ong, L. K., Effendi, C., Kurniawan, A., Lin, C. X., Zhao, X. S., & Ismadji, S. (2013b). Optimization of catalyst-free production of biodiesel from Ceiba pentandra (kapok) oil with high free fatty acid contents. *Energy, 57*, 615-623.

Ortiz-Martínez, V., Salar-García, M., Palacios-Nereo, F., Olivares-Carrillo, P., Quesada-Medina, J., de los Ríos, A., et al. (2016). In-depth study of the transesterification reaction of Pongamia pinnata oil for biodiesel production using catalyst-free supercritical methanol process. *The Journal of Supercritical Fluids, 113*, 23-30.

Öztürk, E. (2015). Performance, emissions, combustion and injection characteristics of a diesel engine fuelled with canola oil–hazelnut soapstock biodiesel mixture. *Fuel Processing Technology, 129*, 183-191.

Pagliaro, M., Ciriminna, R., Kimura, H., Rossi, M., & Della Pina, C. (2007). From glycerol to value-added products. *Angewandte Chemie International Edition, 46*(24), 4434-4440.

Palanivelrajan, A., & Anbarasu, G. (2016). Experimental Investigation of Performance and Emission Characteristics of Cebia petandra Biodiesel in CI Engine. *International Journal of ChemTech Research, 9*(4), 230-238.

Pereira, R. C., Skrobot, V. L., Castro, E. V., Fortes, I. C., & Pasa, V. M. (2006). Determination of gasoline adulteration by principal components analysis-linear discriminant analysis applied to FTIR spectra. *Energy & Fuels, 20*(3), 1097-1102.

Pérez, Á., Casas, A., Fernández, C. M., Ramos, M. J., & Rodríguez, L. (2010). Winterization of peanut biodiesel to improve the cold flow properties. *Bioresource Technol, 101*(19), 7375-7381.

Pranowo, D. (2014). Pembuatan Biodiesel Dari Kemiri Sunana Dan Pemanfaatan Hasil Samping: IAARD Press.

Pukale, D. D., Maddikeri, G. L., Gogate, P. R., Pandit, A. B., & Pratap, A. P. (2015). Ultrasound assisted transesterification of waste cooking oil using heterogeneous solid catalyst. *Ultrasonics Sonochemistry, 22*, 278-286.

Rabelo, S. N., Ferraz, V. P., Oliveira, L. S., & Franca, A. S. (2015). FTIR analysis for quantification of fatty acid methyl esters in biodiesel produced by microwave-assisted transesterification. *International Journal of Environmental Science and Development, 6*(12), 964.

Rabiah Nizah, M. F., Taufiq-Yap, Y. H., Rashid, U., Teo, S. H., Shajaratun Nur, Z. A., & Islam, A. (2014). Production of biodiesel from non-edible Jatropha curcas oil via transesterification using Bi2O3–La2O3 catalyst. *Energy Conversion Management, 88*, 1257-1262.

Rajasekar, E., & Selvi, S. (2014). Review of combustion characteristics of CI engines fueled with biodiesel. *Renewable and Sustainable Energy Reviews, 35*(0), 390-399.

Rakopoulos, C. D., Antonopoulos, K. A., Rakopoulos, D. C., Hountalas, D. T., & Giakoumis, E. G. (2006). Comparative performance and emissions study of a direct injection Diesel engine using blends of Diesel fuel with vegetable oils or bio-diesels of various origins. *Energy Conversion and Management, 47*(18–19), 3272-3287.

Ramadhas, A., Jayaraj, S., & Muraleedharan, C. (2004). Use of vegetable oils as IC engine fuels—a review. *Renewable Energy, 29*(5), 727-742.

Ramadhas, A. S., Jayaraj, S., & Muraleedharan, C. (2005). Biodiesel production from high FFA rubber seed oil. *Fuel, 84*(4), 335-340.

Ramírez-Verduzco, L. F., Rodríguez-Rodríguez, J. E., & del Rayo Jaramillo-Jacob, A. (2012). Predicting cetane number, kinematic viscosity, density and higher heating value of biodiesel from its fatty acid methyl ester composition. *Fuel, 91*(1), 102-111.

Rashid, U., & Anwar, F. (2008). Production of biodiesel through optimized alkaline-catalyzed transesterification of rapeseed oil. *Fuel, 87*(3), 265-273.

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

Sakai, T., Kawashima, A., & Koshikawa, T. (2009). Economic assessment of batch biodiesel production processes using homogeneous and heterogeneous alkali catalysts. *Bioresource Technology, 100*(13), 3268-3276.

Salahi, A., Abbasi, M., & Mohammadi, T. (2010). Permeate flux decline during UF of oily wastewater: Experimental and modeling. *Desalination, 251*(1), 153-160.

Salar-García, M., Ortiz-Martínez, V., Olivares-Carrillo, P., Quesada-Medina, J., de los Ríos, A., & Hernández-Fernández, F. (2016). Analysis of optimal conditions for biodiesel production from Jatropha oil in supercritical methanol: quantification of thermal decomposition degree and analysis of FAMEs. *The Journal of Supercritical Fluids, 112*, 1-6.

Salimon, J., & Kadir, K. A. A. (2005). Fatty acid composition and physicochemical properties in Kekabu seed oil. *Sains Malaysiana, 34*(2), 117-120.

Sanford, S. D., White, J. M., Shah, P. S., Wee, C., Valverde, M. A., & Meier, G. R. (2009). Feedstock and biodiesel characteristics report. *Renewable Energy Group, 416*, 1-136.

Santana, G., Martins, P., Da Silva, N. d. L., Batistella, C., Maciel Filho, R., & Maciel, M. W. (2010). Simulation and cost estimate for biodiesel production using castor oil. *Chemical Engineering Research and Design, 88*(5), 626-632.

Sarin, R., Sharma, M., Khan, A. A. (2010). Terminalia belerica Roxb. seed oil: A potential biodiesel resource. *Bioresource Technology, 101*(4), 1380-1384.

Sarin, R., Sharma, M., Khan, A.A. (2009). Studies on Guizotia abyssinica L. oil: Biodiesel synthesis and process optimization. *Bioresource Technology, 100*(18), 4187-4192.

Sarma, A. K., Konwer, D.,Bordoloi, P. K. (2005). A Comprehensive Analysis of Fuel Properties of Biodiesel from Koroch Seed Oi. *Energy & Fuels, 19*(2), 656-657.

Sedman, J., van De Voort, F., & Ismail, A. A. (2000). Simultaneous determination of lodine value and trans content of fats and oils by single-bounce horizontal attenuated total reflectance fourier transform infrared spectroscopy. *Journal of the American Oil Chemists' Society, 77*(4), 399-403.

Sethusundaram, P., Vijayakumar, M., & Prasanna, N. EFFECT OF STERCULIA FOETIDA BIODIESEL ON SINGLE CYLINDER FOUR STROKE DIESEL ENGINE PERFORMANCE AND EMISSIONS.

Shafie, S. M. (2015). *An Integrated Approach for Techno-economic and Environmental Analysis of Power Generation from Paddy Residue in Malaysia.* Universiti Malaya.

Shahir, S. A., Masjuki, H. H., Kalam, M. A., Imran, A., Fattah, I. M. R., & Sanjid, A. (2014). Feasibility of diesel–biodiesel–ethanol/bioethanol blend as existing CI engine fuel: An assessment of properties, material compatibility, safety and combustion. *Renewable and Sustainable Energy Reviews, 32*(0), 379-395.

Shamsuddin, A. H. (2012). Development of renewable energy in Malaysia-strategic initiatives for carbon reduction in the power generation sector. *Procedia Engineering, 49*, 384-391.

Shang, Q., Jiang, W., Lu, H., Liang, B. (2010). Properties of Tung oil biodiesel and its blends with 0# diesel. *Bioresource Technology, 101*(2), 826-828.

Sharma, Y., & Singh, B. (2011). Optimization of two step karanja biodiesel synthesis under microwave irradiation Original Research Article Fuel Processing Technology. *Volume, 92*, 100-105.

Sharma, Y. C., Singh, B. (2010). An ideal feedstock, kusum (Schleichera triguga) for preparation of biodiesel: Optimization of parameters. *Fuel, 89*(7), 1470-1474.

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

Silitonga, A., Masjuki, H., Mahlia, T., Ong, H., Chong, W., & Boosroh, M. (2013a). Overview properties of biodiesel diesel blends from edible and non-edible feedstock. *Renewable and Sustainable Energy Reviews, 22*, 346-360.

Silitonga, A., Ong, H., Mahlia, T., Masjuki, H., & Chong, W. (2013b). Characterization and production of Ceiba pentandra biodiesel and its blends. *Fuel, 108*, 855-858.

Silitonga, A., Ong, H., Masjuki, H., Mahlia, T., Chong, W., & Yusaf, T. F. (2013c). Production of biodiesel from Sterculia foetida and its process optimization. *Fuel, 111*, 478-484.

Silitonga, A. S., Masjuki, H. H., Mahlia, T. M. I., Ong, H. C., Chong, W. T., & Boosroh, M. H. (2013d). Overview properties of biodiesel diesel blends from edible. *Renewable and Sustainable Energy Reviews*.

Silitonga, A. S., Masjuki, H. H., Ong, H. C., Kusumo, F., Mahlia, T. M. I., & Bahar, A. H. (2016a). Pilot-scale production and the physicochemical properties of palm and Calophyllum inophyllum biodiesels and their blends. *Journal of Cleaner Production, 126*, 654-666.

Silitonga, A. S., Masjuki, H. H., Ong, H. C., Yusaf, T., Kusumo, F., & Mahlia, T. M. I. (2016b). Synthesis and optimization of Hevea brasiliensis and Ricinus communis as feedstock for biodiesel production: A comparative study. *Industrial Crops and Products, 85*, 274-286.

Silitonga, A. S., Ong, H. C., Mahlia, T. M. I., Masjuki, H. H., & Chong, W. T. (2013e). Characterization and production of Ceiba pentandra biodiesel and its blends. *Fuel, 108*(0), 855-858.

Singh, A. K., Fernando, S. D., & Hernandez, R. (2007). Base-catalyzed fast transesterification of soybean oil using ultrasonication. *Energy & Fuels, 21*(2), 1161-1164.

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

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

Sivakumar, P., Sindhanaiselvan, S., Gandhi, N. N., Devi, S. S., & Renganathan, S. (2013). Optimization and kinetic studies on biodiesel production from underutilized Ceiba Pentandra oil. *Fuel, 103*, 693-698.

Smith, E. G., Janzen, H., & Newlands, N. K. (2007). Energy balances of biodiesel production from soybean and canola in Canada. *Can J Plant Sci, 87*(4), 793-801.

Soares, I. P., Rezende, T. F., Silva, R. C., Castro, E. V. R., & Fortes, I. C. (2008). Multivariate calibration by variable selection for blends of raw soybean oil/biodiesel from different sources using Fourier transform infrared spectroscopy (FTIR) spectra data. *Energy & Fuels, 22*(3), 2079-2083.

Sorate, K. A., & Bhale, P. V. (2015). Biodiesel properties and automotive system compatibility issues. *Renewable and Sustainable Energy Reviews, 41*, 777-798.

Soriano Jr, N. U., Migo, V. P., & Matsumura, M. (2006). Ozonized vegetable oil as pour point depressant for neat biodiesel. *Fuel, 85*(1), 25-31.

Sotoft, L. F., Rong, B.-G., Christensen, K. V., & Norddahl, B. (2010). Process simulation and economical evaluation of enzymatic biodiesel production plant. *Bioresource Technology, 101*(14), 5266-5274.

Subroto, E., Manurung, R., Heeres, H. J., & Broekhuis, A. A. (2015). Optimization of mechanical oil extraction from Jatropha curcas L. kernel using response surface method. *Industrial Crops and Products, 63*, 294-302.

Takase, M., Feng, W., Wang, W., Gu, X., Zhu, Y., Li, T., et al. (2014). Silybum marianum oil as a new potential non-edible feedstock for biodiesel: A comparison of its production using conventional and ultrasonic assisted method. *Fuel Processing Technology, 123*, 19-26.

Takase, M., Zhao, T., Zhang, M., Chen, Y., Liu, H., Yang, L., et al. (2015). An expatiate review of neem, jatropha, rubber and karanja as multipurpose non-edible biodiesel resources and comparison of their fuel, engine and emission properties. *Renewable and Sustainable Energy Reviews, 43*, 495-520.

Tan, Y. H., Abdullah, M. O., Nolasco-Hipolito, C., & Taufiq-Yap, Y. H. (2015). Waste ostrich-and chicken-eggshells as heterogeneous base catalyst for biodiesel production from used cooking oil: Catalyst characterization and biodiesel yield performance. *Applied Energy, 160*, 58-70.

Taufiq-Yap, Y. H., Teo, S. H., Rashid, U., Islam, A., Hussien, M. Z., & Lee, K. T. (2014). Transesterification of Jatropha curcas crude oil to biodiesel on calcium lanthanum mixed oxide catalyst: effect of stoichiometric composition. *Energy Conversion and Management, 88*, 1290-1296.

Teixeira, L. S., Assis, J. C., Mendonça, D. R., Santos, I. T., Guimarães, P. R., Pontes, L. A., et al. (2009). Comparison between conventional and ultrasonic preparation of beef tallow biodiesel. *Fuel Processing Technology, 90*(9), 1164-1166.

Thiruvengadaravi, K., Nandagopal, J., Baskaralingam, P., Bala, V. S. S., & Sivanesan, S. (2012). Acid-catalyzed esterification of karanja (Pongamia pinnata) oil with high free fatty acids for biodiesel production. *Fuel, 98*, 1-4.

Torres-Rodríguez, D. A., Romero-Ibarra, I. C., Ibarra, I. A., & Pfeiffer, H. (2016). Biodiesel production from soybean and Jatropha oils using cesium impregnated sodium zirconate as a heterogeneous base catalyst. *Renewable Energy, 93*, 323-331.

Tosun, E., Yilmaz, A. C., Ozcanli, M., & Aydin, K. (2014). Determination of effects of various alcohol additions into peanut methyl ester on performance and emission characteristics of a compression ignition engine. *Fuel, 126*, 38-43.

U.S., N. P. G. S. (1966). Reutealis trisperma. 2016, from https://npgsweb.ars-grin.gov/gringlobal/taxonomydetail.aspx?id=400318

Vairamuthu, G., Sundarapandian, S., & Thangagiri, B. (2016). Experimental investigations on the influence of properties of Calophyllum inophyllum biodiesel on performance, combustion, and emission characteristics of a DI diesel engine. *International Journal of Ambient Energy, 37*(6), 616-624.

Van Gerpen, J. H., & He, B. B. (2014). 14 - Biodiesel and renewable diesel production methods. In K. Waldron (Ed.), *Advances in Biorefineries* (pp. 441-475): Woodhead Publishing.

Varatharajan, K., & Cheralathan, M. (2013). Effect of aromatic amine antioxidants on NOx emissions from a soybean biodiesel powered DI diesel engine. *Fuel Processing Technology, 106*(0), 526-532.

Verduzco, L. F. R. (2013). Density and viscosity of biodiesel as a function of temperature: empirical models. *Renewable and Sustainable Energy Reviews, 19*, 652-665.

Vorasingha, A. (2017). *Biodiesel Production from Sterculia foetida Oil by Using Solid Support Catalyst.* Paper presented at the Applied Mechanics and Materials.

Wahyudi, A., Ferry, Y., Herman, M., Pranowo, D., & Ardana, K. (2009). Proyeksi produksi biodiesel. *Kemiri Sunan Penghasil Biodiesel, Solusi Masalah energi Masa depan. Suatu bunga Rampai. Unit Penerbitan Balittri, 2009*, 119-126.

Wirawan, S. S. (2007). *Future biodiesel research in Indonesia.* Paper presented at the Asian Science and Technology Seminar, Jakarta, 2007, Available at:< http://www.jst.go.jp/asts/asts_j/files/ppt/16_ppt.pdf.

Wulandari, W. S., Darusman, D., & Cecep Kusmana, W. (2014). Land Suitability Analysis of Biodiesel Crop Kemiri Sunan (Reutealis trisperma (Blanco) Airy Shaw) in The Province of West Java, Indonesia. *Journal of Environment and Earth Science, 4*(21), 27-37.

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

Yang, F. X., Su, Y.Q., Li, X.H., Zhang, Q.Sun., R.C. (2009). Preparation of biodiesel from Idesia polycarpa var. vestita fruit oil. *Industrial Crops and Products, 29*(2-3), 622-628.

Yee, K. F., Tan, K. T., Abdullah, A. Z., & Lee, K. T. (2009). Life cycle assessment of palm biodiesel: revealing facts and benefits for sustainability. *Applied Energy, 86*, S189-S196.

Yin, X., You, Q., Ma, H., Dai, C., Zhang, H., Li, K., et al. (2015). Biodiesel production from soybean oil deodorizer distillate enhanced by counter-current pulsed ultrasound. *Ultrason Sonochem, 23*, 53-58.

You, Y.-D., Shie, J.-L., Chang, C.-Y., Huang, S.-H., Pai, C.-Y., Yu, Y.-H., et al. (2007). Economic Cost Analysis of Biodiesel Production: Case in Soybean Oil†. *Energy & Fuels, 22*(1), 182-189.

Yu, X.-H., Rawat, R., & Shanklin, J. (2011). Characterization and analysis of the cotton cyclopropane fatty acid synthase family and their contribution to cyclopropane fatty acid synthesis. *BMC plant biology, 11*(1), 97.

Yusuf, N., & Kamarudin, S. K. (2013). Techno-economic analysis of biodiesel production from Jatropha curcas via a supercritical methanol process. *Energy Conversion and Management, 75*, 710-717.

Yusuf, N., Kamarudin, S. K., & Yaakub, Z. (2011). Overview on the current trends in biodiesel production. *Energy Conversion and Management, 52*(7), 2741-2751.

Appendixes

Appendix A

Related Publication

Teuku Meurah Indra Riayatsyah, Hwai Chyuan Ong, Wen Tong Chong, Lisa Aditya, Heri Hermansyah, and Teuku Meurah Indra Mahlia (2017) Life Cycle Cost and Sensitivity Analysis of *Reutealis trisperma* as Non-Edible Feedstock for Future Biodiesel Production. *Energies*, 10 (7); 887; doi:10.3390/en10070877

Article Under Review

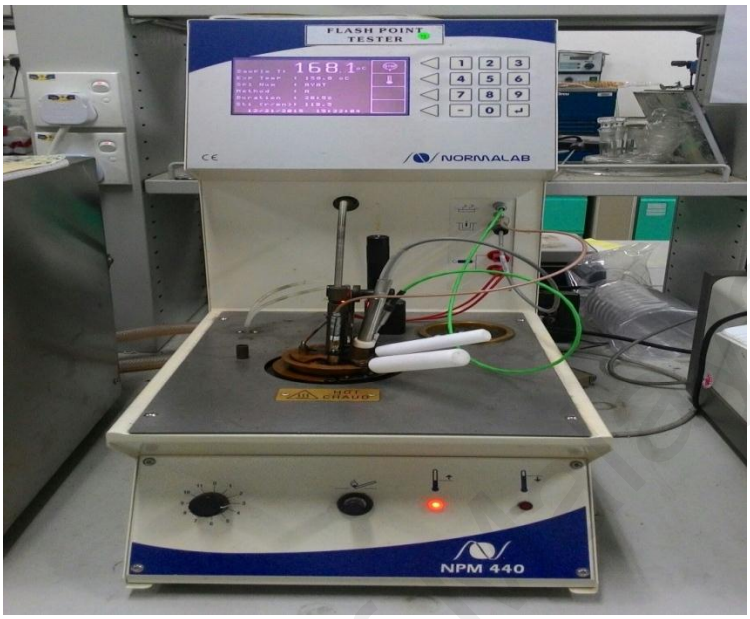
T.M.I. Riayatsyah, Hwai Chyuan Ong, W.T. Chong, F. Kusumo, H. Hermansyah, T.M.I. Mahlia, Investigation of biodiesel production from *Reutealis trisperma* oil using ultrasonication transesterification (EAE-17-0098)

Appendix B: Figure of equipment for biodiesel properties test

Kinematic viscosity

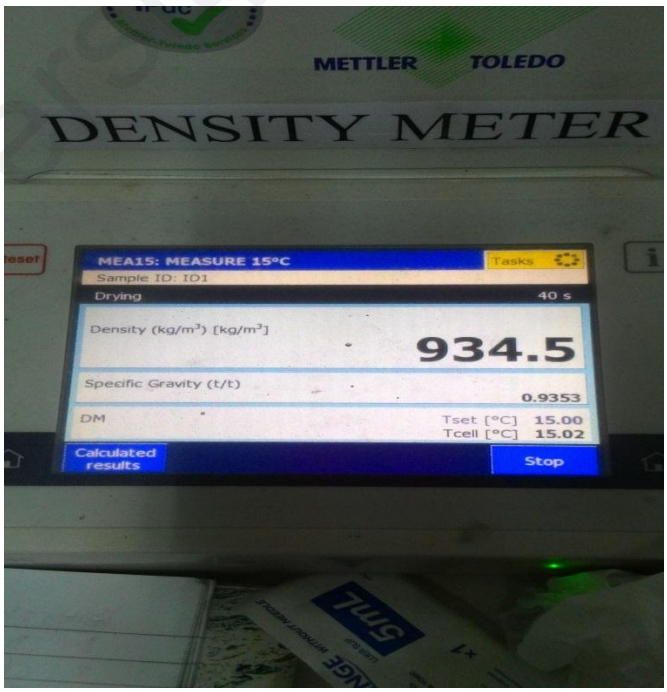
Equipment: Anton Paar SVM 3000 viscometer

Flash point tester



Equipment: Normalab NPM 440 (France)

Density meter tester



Equipment: DM40 Mettler Toledo density meter test (Switzerland)

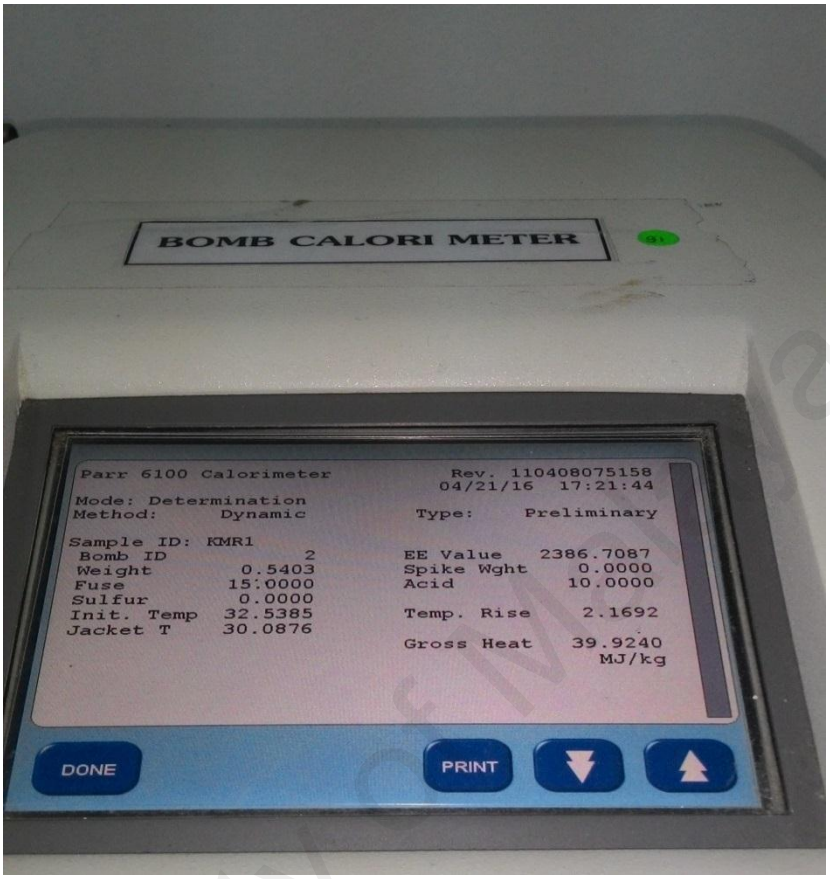
Acid value tester

Equipment: Automation titration rondo 20 (Mettler Toledo, Switzerland)

Copper strip corrosion test

Equipment: Seta copper corrosion bath 11300-0 (StanhopeSeta, UK)

Calorific value tester



Equipment: 6100EF Semi auto bomb calorimeter (Perr, USA)