Faculty of Engineering

Study of Coconut Biodiesel Transesterification Optimum Parameters to Investigate Diesel Engine Performance with Exhaust Gas Emission Analysis

Abdussalam Khan Bin Mustafa Khan

Master of Engineering
2023

Study of Coconut Biodiesel Transesterfication Optimum Parameters to Investigate Diesel Engine Performance with Exhaust Gas Emission Analysis

Abdussalam Khan Bin Mustafa Khan

A thesis submitted

In fulfillment of the requirements for the degree of Master of Engineering

(Mechanical Engineering)

Faculty of Engineering
UNIVERSITI MALAYSIA SARAWAK
2023

DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Salamik

Signature

Name: Abdussalam Khan Bin Mustafa Khan

Matric No.: 16020109

Faculty of Engineering

Universiti Malaysia Sarawak

Date :

ACKNOWLEDGEMENT

I would like to take this opportunity to thank those who have contributed directly or indirectly to this thesis.

My sincere gratitude to my father, Mustafa Khan and my mother, Morni Binti Askha for countless support and encouragement during my period of study. Nevertheless, I would like to thank my supervisor, Assoc Prof Ir Dr Syed Tarmizi Syed Shazali and my ex-supervisor Assoc Prof Dr Abu Saleh Ahmed for the advice and support given during my period of study in Universiti Malaysia Sarawak.

Finally, I would like to thank the management of the Universiti Malaysia Sarawak (UNIMAS) for making it possible for me to complete my study here in Sarawak. Thank you all.

ABSTRACT

Biodiesel is one of the renewable alternative fuels, which can be obtained from vegetable oils or animal fats. Biodiesel's global demand has increased significantly over the last decade. The continuous rise in demand requires new technology to produce biodiesel in a more efficient and environmental way. Current biodiesel technology mainly produces biodiesel from crop oils that are commonly edible. Edible oil such as crude coconut oil (COCO) is used in this study. Titration method was performed to indicate crude coconut oil free fatty acid (FFA) value. FFA value of COCO determines which method of transesterification to be performed. This study focuses on acid/base catalysed transesterification using homogenous catalyst to produce biodiesel (fatty acid methyl ester) (FAME) from COCO. The optimum parameters of coconut biodiesel (CB) production were studied as well as the physicochemical properties, engine performance and emission analysis. Based on titration performed, FFA value was high with 14.82%. The optimum condition for producing coconut biodiesel were determined to be 0.01:1 v: v catalyst to oil ratio, 0.6:1 v: v methanol to oil ratio, with one hour reaction time at 55°C reaction temperature in acid catalysed esterification process. Whereas for base catalysed transesterification process, the optimum parameters were 0.015:1 w/w catalyst to oil ratio, 6:1 w/w methanol to oil ratio with two (2) hours reaction temperature at 60°C. The optimum condition of acid/base catalysed transesterification produces 98% of ester yield and 95% of biodiesel yield. The engine performance result shows that the engine power output and the mechanical efficiency dropped compared to conventional diesel. On the other hand, the specific fuel consumption increases with the increasing biodiesel blend. For emission analysis, the hydrocarbon and carbon monoxide decrease with the increasing biodiesel blend whereas the nitrogen oxides increased.

Keywords: Biodiesel, crude coconut oil, transesterification, engine performance.

Kajian Parameter Optimum Transesterifikasi Biodisel Kelapa Untuk Menyiasat Prestasi Enjin Diesel Dengan Analisis Pelepasan Gas Ekzos

ABSTRAK

Biodiesel adalah salah satu bahan api alternatif yang boleh diperbaharui, yang boleh diperolehi daripada minyak sayuran atau lemak haiwan. Permintaan global biodiesel telah meningkat dengan ketara sepanjang dekad yang lalu. Peningkatan permintaan yang berterusan memerlukan teknologi baharu untuk menghasilkan biodiesel dengan cara yang lebih cekap dan mesra alam. Teknologi biodiesel semasa terutamanya menghasilkan biodiesel daripada minyak tanaman yang lazimnya boleh dimakan. Minyak yang boleh dimakan seperti minyak kelapa mentah (COCO) digunakan dalam kajian ini. Kaedah pentitratan dilakukan untuk menentukan nilai asid lemak bebas (FFA) minyak kelapa mentah. Kajian ini memfokuskan kepada transesterifikasi bermangkin asid/alkali menggunakan mangkin homogen untuk menghasilkan biodiesel (asid lemak metil ester) (FAME) daripada COCO. Parameter optimum pengeluaran biodiesel kelapa (CB) telah dikaji serta sifat fizikokimia, prestasi enjin dan analisa pelepasan asap. Berdasarkan pentitratan yang dilakukan, nilai FFA adalah tinggi iaitu 14.82%. Keadaan optimum untuk menghasilkan biodiesel kelapa ditentukan ialah 0.01:1 v:v nisbah mangkin kepada minyak, 0.6:1 v/v nisbah metanol kepada minyak, dengan masa tindak balas satu jam pada suhu tindak balas 55°C dalam proses pengesteran bermangkin asid. Manakala bagi proses transesterifikasi bermangkin berasaskan, parameter optimum ialah 0.015:1 b/b nisbah pemangkin kepada minyak, 6:1 b/b nisbah metanol kepada minyak dengan dua (2) jam suhu tindak balas pada 60°C. Keadaan optimum transesterifikasi bermangkin asid/alkali menghasilkan 98% hasil ester dan 95% hasil biodiesel. Keputusan prestasi enjin menunjukkan bahawa kuasa pengeluaran enjin dan kecekapan mekanikal menurun

berbanding diesel konvensional. Sebaliknya, penggunaan bahan api khusus meningkat dengan peningkatan campuran biodiesel. Untuk analisis pelepasan, hidrokarbon dan karbon monoksida berkurangan dengan campuran biodiesel yang meningkat manakala nitrogen oksida meningkat.

Kata kunci: *Biodiesel, minyak kelapa mentah, transesterifikasi, prestasi enjin.*

TABLE OF CONTENTS

		Page
DECLARATION		i
ACKNOWLEDGEMENT		ii
ABSTRACT		iii
ABSTRAK		v
TABLE OF CONTENTS		vii
LIST OF TABLES		xi
LIST OF FIGURES		xi
LIST OF ABBREVIATIONS		xiiv
CHAPTER 1 : INTRODUCTION		1
1.1	The Propitious of Biodiesel as an Alternative Fuel	1
1.2	Problem Statement	3
1.3	Research Hypothesis	7
1.4	Objectives	7
1.5	Organization of Thesis	8
CHAPTER 2 : LITERATURE REVIEW		9
2.1	Overview: Global Biodiesel Phenomena	9
2.2	Distribution and Physicochemical Properties of Biodiesel Feedstock	11
2.3	Coconut As Biodiesel	12

2.4 The Properties of Conventional Diesel Fuel, Biodiesel Standard (ASTM & EN) 18

2.5 Catalyst Application 22

2.6 Transesterification 25

2.6.1 One-Step Transesterification 26

2.6.2 Two Step Transesterification 27

2.7 Direct Use and Blending 30

2.8 Microemulsion 32

2.9 Pyrolysis 32

2.10 Diesel Engine Performance and Exhaust Emission Analysis 33

CHAPTER 3 : METHODOLOGY 42

3.1 Introduction 42

3.2 Laboratory 43

3.3 Raw Materials 43

3.4 Crude Coconut Oil Filtration 44

3.5 Free Fatty Acid Analysis 45

3.6 Transesterification 47

3.6.1 Acid Pre-treatment (Esterfication) 47

3.6.2 Base Transesterification 50

3.7 Physicochemical Properties Determination 53

3.8 Biodiesel Blending 53

3.9 Engine Performance Test 54

CHAPTER 4 : RESULT AND DISCUSSION 56

4.1 Crude Coconut Oil Acid Value Determination 56

4.2 Biodiesel Production 57

4.2.1 One Step Transesterification 57

4.2.2 Two Step Transesterification 58

4.2.2.1 Effects of Catalyst Concentration on Coconut Biodiesel Yield 58

4.2.2.2 Effects of Methanol to Oil Ratio on Coconut Biodiesel Yield 60

4.2.2.3 Effect of Reaction Time on Coconut Biodiesel Yield 64

4.2.2.4 Effect of Reaction Temperature on Coconut Biodiesel Yield 66

4.3 Characterization of Coconut biodiesel 68

4.3.1 Physicochemical Properties of Coconut Crude Oil and Coconut biodiesel 68

4.4 Diesel Engine Mechanical Performance Optimization 69

4.5 Diesel Engine Exhaust Gas Emission Ooptimization 75

CHAPTER 5 : CONCLUSION AND RECOMMENDATION 77

5.1 Conclusion 77

5.2 Biodiesel Conversion 77

5.3 Optimum Conditions for Coconut Biodiesel Conversion 78

5.4 Coconut Biodiesel Properties Analysis 79

5.5 Diesel Engine Performance by Using Coconut Biodiesel Blends 79

5.6 Recommendations 80

5.7 Future Research 81

REFERENCES 82

LIST OF TABLES

Page

Table 1.1	Emission Comparison of Biodiesel and Diesel (Knothe, 2010)	4
Table 2.1	The Fuel Properties of Conventional Diesel fuel and Blends of Coconut Metyl Ester (Malik et al., 2017)	19
Table 2.2	Physico-chemical Properties of Coconut Oil and Coconut Biodiesel. (Lugo-Méndez et al., 2021)	21
Table 3.1	Specification of Chemicals	46
Table 3.2	Esterification Experimental Matrix Process Parameters (Mohiddin, 2018)	47
Table 3.3	Esterification Reaction Condition Matrix (Khan et al., 2021)	47
Table 3.4	Transesterification Experimental Matrix Process Parameters (Mohiddin, 2018)	50
Table 3.5	Transesterification Reaction Condition Matrix (Khan et al., 2021)	51
Table 3.6	Coconut Biodiesel Blend Formulation (Reddy et al., 2017b)	54
Table 3.7	Calculation Formula Summary for Diesel Engine Performance (Reddy et al., 2015)	55
Table 4.1	Results of Titration	56
Table 4.2	COCO Acid Value and FFA Content	56
Table 4.3	Physicochemical Properties of Coconut Crude Oil and Coconut Biodiesel	69
Table 4.4	Experimental Results of Diesel Engine Testing for B0 to B50 Blends	69
Table 4.5	Results of Emission Analysis of Petrodiesel dan Coconut Biodiesel	75

LIST OF FIGURES

Page

Figure 2.1	Biofuel classification (Singh Sikarwar et al., 2017)	11
Figure 2.2	Major Production of Coconut From Various Countries From 2014-2015 (Malik et al., 2017)	13
Figure 2.3	Different Catalyst Used Biodiesel Production (Fattah et al., 2020)	25
Figure 2.4	Transesterification Process. Process A : Two-step process. Process B : One step Process. (Fattah et al., 2014; Mofijur et al., 2014)	26
Figure 2.5	Graph of HC Emission versus Engine Speed (Mofijur et al., 2014)	40
Figure 3.1	Chronology of Biodiesel Production and Analysis	42
Figure 3.2	Crude Coconut Oil Filtration Steps	44
Figure 3.3	FFA Experimental Steps	45
Figure 3.4	Esterification Process Steps (Bello et al., 2015)	49
Figure 3.5	Transesterification Process Steps (Reddy et al., 2017b)	51
Figure 4.1	Graph of FFA Content versus Catalyst to Oil Ratio for Acid-Catalyzed Esterfication	58
Figure 4.2	Graph of Coconut Biodiesel Yield versus Catalyst to Oil Ratio for Base Catalyzed Transesterification	59
Figure 4.3	Graph of Acid Value and FFA Percentage versus Methanol to Oil Ratio for Acid Catalysed Esterification	60
Figure 4.4	Graph of Ester Yield versus Methanol to Oil Ratio for Acid Catalysed Transesterification	61
Figure 4.5	Graph of Coconut Biodiesel Yield versus Methanol to Oil Ratio for Base Catalysed Transesterification	63
Figure 4.6	Graph of Ester Yield versus Reaction Time	64
Figure 4.7	Graph of Coconut Biodiesel Yield versus Reaction Time	65
Figure 4.8	Graph of Ester Yield versus Reaction Temperature	66
Figure 4.9	Graph of Coconut Biodiesel Yield versus Reaction Temperature	67

Figure 4.10 Graph of Coconut Biodiesel Blends versus Engine Power Output 70

Figure 4.11 Coconut Biodiesel Blends versus Specific Fuel Consumption 71

Figure 4.12 Coconut Biodiesel Blends versus Brake Horsepower 73

Figure 4.13 Coconut Biodiesel Blends versus Mechanical Efficiency 75

LIST OF ABBREVIATIONS

AFR	Air Fuel Ratio
AI	Acid Index
ASTM	American Society for Testing and Materials
BHP	Brake Horse Power
BSFC	Break-Specific Fuel Consumption
$C_{20}H_{14}O_4$	Phenolphthalein
C_2H_5OH	Ethanol
$C_4H_{10}O$	Di-ethyl Ether
CB	Coconut Biodiesel
CDF	Commercial Diesel Fuel
CFPP	Cold Filter Plugging Point
CH_3OH	Methanol
CME	Coconut Methyl Ester
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COCO	Crude Coconut Oil

CP	Cloud Point
CRDI	Common Rail Direct Injection
CTO	Catalyst to Oil ratio
EN	European Standards
FAME	Fatty Acid Metyhl Esters
FCR	Fuel Consumption Rate
FFA	Free Fatty Acid
FT-IR	Fourier Transform Infrared
GHG	Greenhouse gas
H_2SO_4	Sulphuric Acid
HC	Hydrocarbon
HHV	High Heating Value
HV	Heating Value
IEA	International Energy agency
II	Iodine Index
KOH	Potassium Hydroxide
kPa	Kilopascal
kW	Kilowatt
LPM	Liter Per Minute
MTO	Methanol to Oil ratio

NaOH	Sodium Hydroxide
NO_X	Nitrogen Oxide
PD	Petrodiesel
PM	Particulate Matters
PP	Pour Point
RPM	Rounds Per Minute
RT1	Reaction time
RT2	Reaction temperature
SFC	Specific Fuel Consumption
SI	Saponification Index
SO_2	Sulphur Dioxide
WCO	Waste Cooking Oil

CHAPTER 1

INTRODUCTION

1.1 The Propitious of Biodiesel as an Alternative Fuel

The second most significant source of greenhouse gas emissions (GHG) is using fossil fuels in transportation (Espinoza et al., 2017). As a result, the automotive industry actively focuses on finding clean and renewable alternatives to fossil fuels (Veza et al., 2021a). As alternative and renewable energy sources, biofuels such as alcohol (Aditiya et al., 2019; Veza et al., 2020) and biodiesel (Silitonga et al., 2015) have gained appeal. The upward trend is anticipated to continue, with biofuels forecast to make up around 7% of road transportation in future years to come (Martinot et al., 2009).

Despite being a clean and renewable fuel, it is relatively has higher viscosities, around 11–17 times greater than those of gasoline and diesel, will result in several issues with fuel atomization, combustion, and pumping (Mahlia et al., 2020). Choking fuel injectors is another typical issue (Kumar et al., 2015). Additionally, biodiesel in an unmodified diesel engine could produce excessive engine wear (Dhar & Agarwal, 2014). As a result, it's critical to enhance the physicochemical characteristics of biodiesel to ensure compatibility with diesel engines (Veza et al., 2021b). It should be noted that modest adjustments can be needed to guarantee biodiesel compatibility with modern diesel engines.

It has good storage qualities like petroleum fuel and may be kept anywhere. Compared to traditional diesel fuel, handling, moving, and storing biodiesel has fewer chemical risks and hazards. Transesterification is used to make biodiesel from various feedstocks, including waste oil, non-edible oil, and edible oil. Diesel-biodiesel blends from

vegetable oils burn more cleanly than regular diesel, producing less carbon, particulate matter, unburned and burned hydrocarbons (Teixeira et al., 2012).

Edible oil or animal fat interacts with an alcohol, such as methanol, in the presence of a catalyst that typically equates to a strongly basic, such as sodium or potassium hydroxide, to form biodiesel through the reversible transesterification reaction. Because of its higher physical and chemical similarities to diesel, transesterification is the best method for producing biodiesel (Farobie & Matsumura, 2017).

Coconut oil is one vegetable oil used as a raw material to make biodiesel. Coconut oil is inexpensive, has a high concentration of free fatty acids (FFA), and has few uses other than being consumed as food. In Asia, Central and South America, and some parts of Africa, coconut, a native of tropical eastern regions, is renowned for providing large yields per hectare. A coconut palm has a lifespan of 70 years, may produce up to 75 fruits annually, flourishes on nutrient-poor soil, and is simple to harvest (Santos, 2012). As a result, coconut oil has a great potential to lower the price of producing biodiesel.

Research by Bello et al. (2015) has shown that coconut diesel, produced through transesterification with methanol, has great potential as a biodiesel product. Similarly, studies conducted by Nakpong & Wootthikanokkhan (2010) and Chinnamma et al. (2015) have also demonstrated the promising potential of coconut diesel as a biodiesel. Globally, more than 350 oil-producing crops are currently being explored as potential sources of triglycerides for biodiesel production. The key to producing biodiesel is choosing an appropriate feedstock (Subbarayan et al., 2016). A viable feedstock should ideally satisfy industrial-scale production and low associated costs. The local weather, soil quality, topography, and farming practices used by the nation all impact how affordable and

accessible the raw materials for biodiesel synthesis are. There is currently a market for biodiesel production from used cooking oil and animal fats, but choosing the suitable feedstock is crucial because it determines 70% of the cost of the finished product (Knothe, 2010).

This study investigates biodiesel synthesis from crude coconut oil (COCO), an edible oil. The base-catalyzed and acid/base-catalyzed transesterification processes created the coconut biodiesel (CB). To maximize the conversion of COCO into CB, the critical reaction parameters, including the oil to methanol volume ratio and catalyst concentration, were investigated. CB's physicochemical fuel qualities were examined utilizing tools constructed under EN and ASTM standards. Blends of CB and petrodiesel (PD) were used to investigate the performance of diesel engines.

1.2 Problem Statement

Biodiesel is a substitute fuel for diesel because it is non-toxic, biodegradable, eco-friendly, and renewable (Qiang Tan et al., 2012). Biodiesel has gained much attention from researchers worldwide because of its environmental impact and sustainability (Mofijur et al., 2013).

The use of biodiesel nowadays is very beneficial to the environment and the community. This is because the use of biodiesel will reduce the emission of carbon monoxide (CO), hydrocarbon, sulfur, polycyclic aromatic hydrocarbon (PAH), smoke, and noise in diesel engines compared with petrol diesel. However, the NO_x emission of biodiesel is higher than petrol diesel.

Table 1.1 shows the emission study of biodiesel blends of B20 and B100. From the result shown, consumption of blend B100 shows lower emissions compared to conventional diesel except for NO_x. Polycyclic aromatic hydrocarbon (PAH), identified as the root of cancer, shows a decrease of 80% in biodiesel emission (Mittelbach et al., 2004). Reduction of emissions from pure biodiesel positively impacts the environment, contributing to less global warming. Thus, without any doubt, biodiesel is better than petrol diesel.

Table 1.1 : Emission Comparison of Biodiesel and Diesel (Knothe, 2010)

AVERAGE BIODIESEL EMISSIONS COMPARED TO CONVENTIONAL DIESEL, ACCORDING TO EPA		
Emission Type	**B100**	**B20**
Regulated		
Total Unburned Hydrocarbons**	-67%	-20%
Carbon Monoxide	-48%	-12%
Particulate Matter	-47%	-12%
NOx	+10%	+2%
Non-Regulated		
Sulfates*	-100%	-20%
PAH (Polycyclic Aromatic Hydrocarbons)**	-80%	-13%
nPAH (nitrated PAH's)**	-90%	-50%***
Ozone potential of speciated HC	-50%	-10%

A monoalkyl ether known as biodiesel is created by transesterifying vegetable or animal fats. The current focus is on creating biofuel for transportation that can be produced economically without compromising the availability or demand for food. This is referred to as the second-generation feedstock for biodiesel made from edible oil.

The continuous research in production of biodiesel will aid in the reduction of environmental pollution and the advancement of socioeconomic conditions, particularly in underdeveloped nations (Lugo-Méndez et al., 2021). Edible oils include those from coconut, rapeseed, soybean, sunflower, and others. One of the edible crops with the potential to replace mineral diesel is the coconut, scientifically known as Cocos Nucifera. This is because coconuts are sustainable, readily available, and, most importantly, have lower feedstock

market prices. However, despite its low cost and lack of practical secondary uses, coconut oil contains a high concentration of FFAs and is mainly used as a food product.

The use of coconut oil for energy generation, either in conjunction with or as a replacement for diesel, is receiving more and more attention (Hossain et al., 2012). Numerous incentives and subsidies have helped biofuels gain popularity in the United States and Europe, and several nations are already manufacturing them. It becomes more desirable to use edible oils as fuel as the price differential between petroleum and these fuels grows. The usage of biodiesel fuels based on vegetable oil has grown increasingly important from both an environmental and energy security perspective. Therefore, using coconut oil as a raw material has a significant potential for lowering the cost of producing biodiesel (Lugo-Méndez et al., 2021).

While the research on biodiesel, particularly from coconut oil as a feedstock, has shown promising results in terms of reduced emissions and sustainability, further studies are needed to optimize the production processes, investigate engine performance and emissions under various blend ratios, and assess the potential impact on food security and socioeconomic implications of large-scale coconut oil-based biodiesel production. Addressing these aspects will contribute to a more comprehensive understanding of biodiesel's viability as a renewable and environmentally friendly fuel alternative.

The research on biodiesel and its potential use of coconut oil as a feedstock has been driven by various significant factors. First and foremost, there is a growing concern about environmental issues, such as climate change and pollution, which has led to an urgent need for cleaner and more sustainable energy sources. Biodiesel, including coconut oil-based biodiesel, stands out as a greener alternative to conventional diesel, as it emits lower levels

of harmful substances like carbon monoxide, hydrocarbons, sulfur, PAH, and smoke. Researchers are keen on exploring biodiesel's potential to reduce greenhouse gas emissions and its positive impact on the environment, particularly in the transportation sector.

The finite nature of fossil fuels and the quest for energy security have also been major drivers in biodiesel research. With a focus on renewable and sustainable alternatives, coconut oil, as a plant-based feedstock, holds promise in reducing our dependence on non-renewable fossil fuels. Additionally, the global demand for energy is increasing, necessitating cost-effective alternatives to traditional fuels. Biodiesel production from coconut oil and other edible oils presents an economically viable solution, especially in regions where coconut oil is abundant and easily accessible. Moreover, the pursuit of energy independence drives the exploration of locally available feedstocks like coconut oil for biodiesel production. Many nations seek to reduce their reliance on imported fossil fuels, and biodiesel from coconut oil aligns with this goal, contributing to greater energy self-sufficiency.

While previous research has highlighted the potential benefits of coconut oil-based biodiesel, there are areas that require further investigation. Researchers are actively seeking ways to optimize the production processes, aiming for higher yields and improved purity of biodiesel from coconut oil. Addressing the challenges related to the high free fatty acid content in coconut oil and finding efficient catalysts and process conditions are crucial aspects in this endeavor. Furthermore, in-depth studies on engine performance and emissions using coconut oil-based biodiesel blends, such as B20 and B100, are essential. Understanding the optimal blend ratios that lead to improved engine performance and reduced emissions is vital for promoting the widespread adoption of biodiesel.

As coconut oil is also a significant food product, there is a need to assess the potential impact of increasing its use for biodiesel production on food security, especially in regions where coconuts play a crucial role in the food supply chain. Lastly, exploring the socioeconomic implications of large-scale coconut oil-based biodiesel production is essential to ensure that it brings positive outcomes for local communities, farmers, and the overall economy.

1.3 Research Hypothesis

A promising feedstock for the manufacturing of biodiesel is coconut oil. When transesterified in two processes, the yield of Coconut Biodiesel (CB) is higher when acid/base catalyzed transesterification is carried out compared to alkaline catalyzed transesterification. Physiochemical characteristics of coconut biodiesel (CB) are essential in determining its suitability as a biodiesel fuel and whether it complies with global biodiesel standards. When compared to petrodiesel, coconut biodiesel and its blends demonstrate improved mechanical performance and reduced exhaust gas emissions, making them promising alternatives. However, meeting specific standards is crucial to ensure its widespread acceptance and safe use in various applications.

1.4 Objectives

By using the transesterification process and characterizing the features of coconut oil and coconut biodiesel fuel, this research intends to provide the ideal conditions for manufacturing coconut biodiesel. Another critical step is identifying coconut biodiesel blends with the highest engine performance. The precise goals that are meant to be attained include the following:

i) To produce the biodiesel using a homogenous catalyst and analyze the factors affecting on yield of biodiesel production.

ii) To determine the optimum blend ratio, engine performance, and emission characteristics of Coconut Biodiesel blends.

1.5 Organization of Thesis

The background of the research is laid out in this chapter one to give brief introduction of the main topic of the research along with the research's scope, hypothesis, and objectives. Research gap study are concluded in chapter two where by fundamental principles to current study and review of available literature are well discussed. Chapter three explains technics and methods for catalyst and biodiesel synthesis, engine testing method and exhaust emission test procedures. Results of optimum parameters producing biodiesel, engine test performance and emission analysis are discussed in chapter four. Conclusion of research is presented in the last chapter which is chapter five. Recommendations for future studies are also included in the last chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview: Global Biodiesel Phenomena

The requirement for energy will keep growing over time because we now live in a modern period where many areas of human activity have been automated and powered by technology. The International Energy Outlook 2019 predicts that between 2018 and 2050, global energy consumption will increase by 50% (Chong et al., 2021). The world's energy consumption, or around 80%, currently comes from fossil fuels, including coal, natural gas, and crude oil (Marchetti et al., 2007). According to International Energy Agency report in 2021, the oil demand, the most frequently utilized fossil fuel, is expected to rise further and reach 109.1 million barrels per day by 2045 (IEA, 2021).

Fossil fuel consumption is problematic because of its limited resources and the environmental damage they create when burned. Regeneration of fossil resources happens relatively slowly. According to research on the daily consumption of fossil fuels, the earth's fossil fuel reserves will eventually run out. Renewable energy production becomes a key challenge for global society to minimize fossil-fuel usage when coupled with global warming challenges that are partially driven by greenhouse gas (GHG) emissions from the combustion of fossil fuels (Schmidt & De Rosa, 2020). Due to their renewable nature, bioenergy and biofuels could be a solution to this issue.

There will be less of carbon emissions from biofuels since the carbon dioxide (CO_2) in the atmosphere that plants have absorbed will be released back into the atmosphere during biofuel combustion. Due to its characteristics being remarkably similar to those of fossil

diesel, biodiesel is one of the most commonly utilized biofuels (Aydın, 2020; Mohiddin et al., 2021; Raheem et al., 2020). A non-toxic, sustainable fuel made of vegetable oil, animal fat, and used cooking oil, biodiesel is created using various methods (Bibin et al., 2020).

Compared to diesel fuel, biodiesel can reduce carbon dioxide emissions by 78%, making it the most carbon neutral fuel (Demirbas, 2009). Additionally, biodiesel has shown a very high biodegradability, ranging from 80.4% to 91.2% after 30 days, compared to a meager 24.5% biodegradability of fossil diesel (Fukuda et al., 2001). Utilizing biodiesel has another benefit in it. Its emission content is less damaging to the environment. The central tendency from certain studies suggests that the combustion of biodiesel emits less content of CO, Particulate Matters (PM), Hydrocarbons (HC), and nearly no sulphate emissions. At the same time, it widely varies according to study parameters in engine types and operating conditions. However, using biodiesel typically increases Nitrogen Oxide (NO_x) emission (Pullen & Saeed, 2014).

For the lower air fuel ratio (AFR) and greater energy rates, biodiesel has combustion performance and emission characteristics equivalent to diesel fuel. Except for NO_x, biodiesel use in boilers dramatically lowers harmful emissions to the environment and increases combustion efficiency. Another comparison of biodiesel based on sunflower and soybeans in an experimental boiler yielded various outcomes, with biodiesel combustion being more effective at lower energy rates (Ghorbani et al., 2011). Vegetable oil presence in fuel improved combustion performance, but their high viscosity would be a concern when utilized in high percentage blends.

However, biodiesel needs to be more affordable to generate and use broadly. Since feedstock costs comprise most of the cost of producing biodiesel, the business is now entirely

dependent on them. Some feedstock options, including waste cooking oil and non-edible oil plants, can be found at lower costs but tend to contain more contaminants. Additional processes are required to produce standard quality biodiesel with affordable feedstock to reduce the cost of production, such as by utilizing cutting-edge machine learning and computational analysis technologies (Aghbashlo et al., 2021; Gebremariam & Marchetti, 2018; Rochelle & Najafi, 2019).

2.2 Distribution and Physicochemical Properties of Biodiesel Feedstock

The primary biofuel components of various agricultural biomasses produced via different biochemical pathways are bioethanol, biodiesel, and biogas (Paudel et al., 2017). Due to its production from agricultural leftovers and crops, biodiesel is a derivative of biofuels' first and second generations. Typically, different locations and nations have various biodiesel production sources. Due to the excesses from the manufacture of edible oil, rapeseed is used in European countries. However, soybean is frequently used in biodiesel manufacturing in the United States, which is now the world's top biodiesel producer (Ayetor et al., 2015). The classification of biofuel production from the first to the fourth generation was compiled by Singh Sikarwar et al., (2017) and is depicted in Figure 2.1.

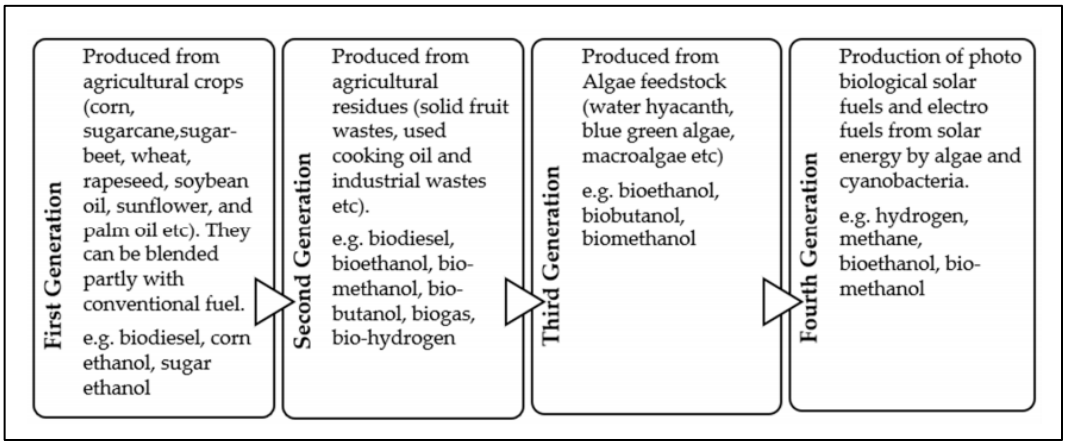

Figure 2.1 : Biofuel classification (Singh Sikarwar et al., 2017)

In Malaysia, Indonesia, and Thailand, surplus palm and coconut oil could be utilized for biodiesel production. To address the food versus fuel competition, researchers have been investigating the use of non-edible seed oils like Karanja (Pongamia second-generation) and Jatropha curcas as alternative raw materials for biodiesel synthesis (Silitonga et al., 2013). Additionally, in Malaysia, the popularity of waste cooking oil (WCO) as a biodiesel alternative to vegetable-based biodiesel is growing due to its cost-effectiveness and the substantial amount of waste production per household. According to Kabir et al. (2014), each home in Malaysia produces an average of 2.34 kg of WCO per month. Furthermore, there is considerable potential in utilizing coconut, scientifically known as Cocos Nucifera, as a feedstock for biodiesel production.

2.3 Coconut As Biodiesel

Researchers worldwide are interested in the advantages of using biodiesel blends made from coconut because it is used in tropical areas as a base fuel. Copra, the dried coconut flesh frequently used in cooking, frying, and being made into soaps, health and beauty items, and crude coconut oil (Raghavan, 2010). The first step in making coconut oil is drying the copra with heat from the sun or burning biomass. Copra was kept in the warehouse for another two to three months to dry further. The dried copra is then sent to a copra cleaner to get rid of any impurities, dirt, and foreign objects before being broken into tiny pieces using a high-speed vertical hammer that range in size from 1.4 mm to 1.6 mm. The copra chunks are heated at 110 °C in a steam cooker for 30 minutes. The copra is then put into an expeller, where a vertical screw and a horizontal screw are used to extract high-pressure oil. Between these temperatures, maximal extraction is achieved, and a light-colored oil is produced. The temperature throughout the extraction process ranges from 93 °C to 102 °C.

With the use of chained mounted scrappers, entrained items are extracted from the coconut oil during the screening process. Before the oil is placed inside a storage tank, it is lastly filtered to eliminate any contaminants further. Three million four hundred sixty thousand tonnes of coconut oil were produced worldwide in total between 2014 and 2015, mostly in nations in the tropics (Chen et al., 2019).

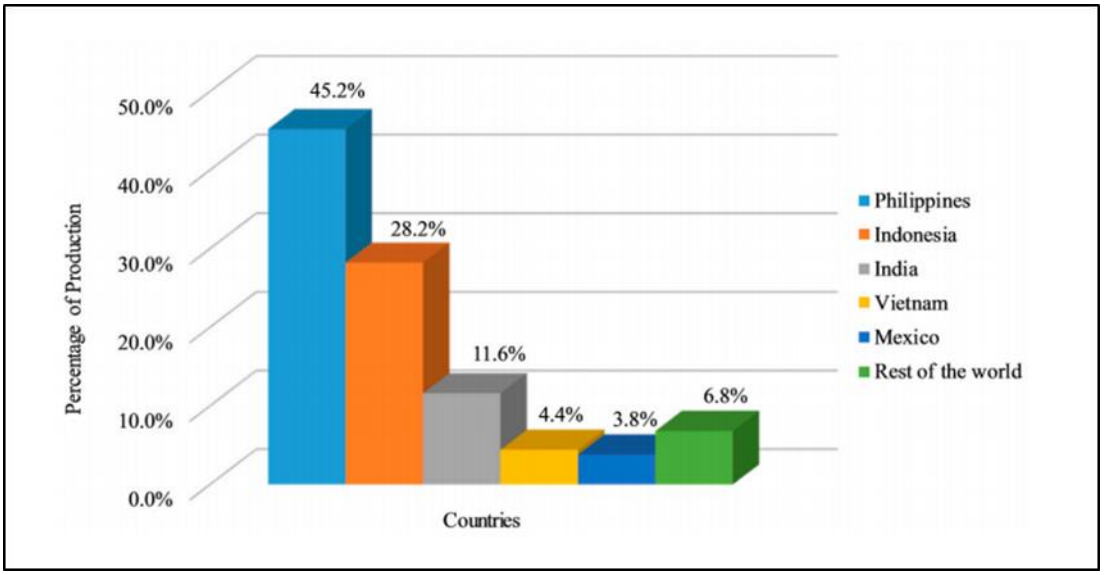

Figure 2.2 : Major Production of Coconut From Various Countries From 2014-2015 (Malik et al., 2017)

Figure 2.2 shows that the Philippines produced 45.2% of all oil, with Indonesia producing 28.2%, India 11.6%, Vietnam 4.4%, Mexico 3.8%, and the rest of the globe producing 6.8%. From USD 1280 per ton in 2014 to USD 1131 per ton in June 2015, then to USD 1039 in August 2015, the average international price for coconut oil dropped (Marina et al., 2009). According to the World Bank Commodities Price Forecast, the average cost of coconut oil will be USD 1112 in 2016 and will steadily drop USD 13 each year during the following three years. Given that these nations contribute significantly to the global production of coconut oil, the drop in the price of coconut oil on the international market

will substantially impact the coconut oil-based industries in Pacific Island nations like Fiji, Papua New Guinea, and the Solomon Islands.

The Pacific Island nations, such as Fiji, Papua New Guinea, and the Solomon Islands, play a significant role in global coconut oil production. However, their reliance on conventional methods for coconut oil production, which involves labor-intensive tasks like gathering, cutting, and drying coconut meat, poses challenges, especially with the recent drop in coconut oil prices. This decline in prices is expected to continue over the next three years, with energies falling by USD 13 (Energies, 2017, 10, 458.3). Consequently, the impact on labor costs could lead to the struggling of related companies, potentially causing some to face extinction.

In this context, the use of coconut oil as biodiesel presents a new opportunity for these island nations to not only generate power but also boost their economy. By diversifying their coconut resources into the biodiesel sector, these nations can reduce their dependency on traditional coconut oil production methods and adapt to the changing market dynamics. Biodiesel production offers a sustainable and environmentally friendly alternative, potentially leading to economic growth and job opportunities in the emerging bioenergy sector.

Biodiesel from coconut oil can be utilized in diesel engines without requiring major adjustments. According to research by Raghavan (2010), Saifuddin et al. (2016), Suryanto et al. (2015), and Llamas et al. (2012), saturated medium chain fatty acids, particularly lauric acid and myristic acid, make up the majority of coconut oil. Additionally, coconut oil has less energy than diesel and solidifies at temperatures lower than 24 °C. The high cetane number of coconut oil, which allows it to burn more quickly than other plant oil biodiesels,

is another benefit of utilizing it as a fuel. Coconut oil has a very high viscosity, resulting in a poor spray pattern and poor volatilization in the fuel injector system. Before spraying into the combustion chamber, coconut oil is often heated using a heat exchanger to reduce its high viscosity (Nevin et al., 2004). Giles discovered in another study that coconut-based biodiesel might adequately burn in a compression ignition diesel engine above 500 °C. He demonstrated that biodiesel made from coconuts would have a shorter ignition delay and would be comparable to diesel at this temperature. The reduced generation of NO_x and CO and the avoidance of carbon deposition on the piston and nozzle valves benefit the shorter combustion delay (Llamas et al., 2012; Raghavan, 2010; Saifuddin et al., 2016; Suryanto et al., 2015).

Other researchers discovered various emission findings from their tests employing mixes of coconut biodiesel. In a one-cylinder, four-stroke diesel engine, Liaquat et al. (2013) examined the use of coconut biodiesel blends B5 and B15 at different throttle settings. Compared to commercial diesel fuel, both biodiesels produced greater exhaust gas temperatures, decreased CO emissions, and slightly increased NO_x emissions (CDF) (Liaquat et al., 2013). Woo and his colleagues (2016) investigated coconut biodiesels of B25 and B40 at various injection timings using the same diesel engine. Their experimental findings showed that for the B25 and B40 blends, NO_x generation was, on average, 8% and 12% less than that of diesel (Woo et al., 2016).

A mechanical combustion device called a fuel oil burner mixes the right amount of fuel oil and air before delivering the mixture to the ignition point in a combustion chamber (Malik et al., 2017). This mixture burns, creating heat used in commercial boilers to produce electricity and building heating systems. Due to rising fuel costs, the need to extend

renewable fuels, utilize waste oils, and give operational assurance against fuel shortages and curtailments, interest in oil burner technology is again rising. Despite the various research to determine the combustion and emission characteristics of biodiesel, it has been reported by other researchers that a commercial oil burner can be used to conduct extensive research on the application of coconut methyl ester (CME) biodiesel (Malik et al., 2017).

A preliminary assessment of the CME acceptability using an oil burner; at various fuel-to-air conditions, the combustion and emission from its use at low blend ratios of B5, B15, and B25 were examined and analysed. These biodiesel blends' exhaust emission concentrations and combustor wall temperatures were compared to CDFs (Habibullah et al., 2015).

Pereira et. al stated that diesel fuel could be blended with coconut oil or coconut biodiesel to burn in combustion engines. Although conceivable, using coconut oil in the engine results in more significant pollutants. In terms of impurities produced, aside from an increase in fuel usage, adding coconut oil generally produces more than adding coconut biodiesel. These substances offer an advantageous oxidative capability that helps to increase engine performance by reducing the specific fuel consumption (SFC). Still, this property only gives the advantage when the mix ratio for coconut oil and biodiesel is less than 10% and 5%, respectively (Pereira et al., 2014).

When coconut biodiesel is added to diesel, NO and NO_x emissions increase. The NO emission increases by 14.9% when diesel is combined with 10% coconut oil (B10). Using 10% coconut biodiesel (B10) causes NO emissions to rise by 9.2%. Diesel emissions of CO are decreased by adding coconut oil (5% to 10%) and coconut biodiesel (5% to 100%). Regarding CO_2 emission, adding coconut oil and coconut biodiesel to diesel increases the

emission of CO_2. However, in most cases, this increase is offset by the plant's ability to absorb CO_2 during the photosynthetic process. Adding coconut oil and coconut biodiesel decreases the emissions of sulfur dioxide (Pereira et al., 2014).

The properties and applicability of the biodiesel produced in this study from coconut oil by homogeneous fundamental catalysis with sodium hydroxide as a catalyst were examined by Lugo-Méndez et al (2021). The following physicochemical parameters of coconut oil and biodiesel were determined: density, kinematic viscosity, refractive index, acidity index, saponification index, iodine index, cetane number, and increased calorific value. The pour, cloud, and cold filter plugging points for coconut biodiesel were also noted as cold flow characteristics. Finally, a regression model was used to analyze and predict the influence of the biodiesel concentration on the density, kinematic viscosity, and heating value of biodiesel blends (Lugo-Méndez et al., 2021).

To assure the conversion of triglycerides into esters, the reaction time for synthesizing biodiesel from coconut oil at 60 °C, with volumetric alcohol: oil ratio of 1:1, and 0.5% of NaOH, is 90 min. Longer reaction times encourage transesterification, the opposite of conversion, rather than the former. Medium-chain saturated methyl esters, which are abundant in coconut oil biodiesel, give it characteristics resembling those of diesel. Most of it is contained under the ASTM and EN standards for biodiesel. Diesel has a calorific value that is 17% higher. Cold areas cannot use biodiesel due to its cloud point (Lugo-Méndez et al., 2021). By adjusting the volumetric proportions of diesel and biodiesel in blends, the density, kinematic viscosity, and high heating value can be altered as they represent weighted averages of the attributes of the two fuels.

Kumar et al. (2021 found that biodiesel is a substitute for diesel manufactured from vegetable or animal fats. In this work, a one-cylinder high-speed diesel engine's characteristics, performance, and exhaust emissions were assessed using fatty acid methyl ester derived from coconut oil as an alternative to diesel. Comparisons were made between operational effectiveness and emission parameters. Although coconut oil has some unfavorable impacts on braking power output and specific fuel consumption, the engine did not have any starting issues. Coconut oil can be a backup fuel in diesel engines to reduce CO and NO_x emissions (Kumar & Raju, 2021).

The current experimental examination on a computerized one-cylinder, water-cooled, direct-ignition four-stroke diesel engine shows the thermal brake efficiency was better when utilizing lower coconut oil biodiesel blends (Sajjadi et al., 2013). Based on their findings, it has been shown that 10–30% oil to diesel blends can be utilized as a diesel substitute without requiring any engine modifications. However, coconut oil diesel, with 40 and 50 percent, has the best performance (Kumar & Raju, 2021).

2.4 The Properties of Conventional Diesel Fuel, Biodiesel Standard (ASTM & EN)

According to a study by Abdul Malik et al. (2017), CDF was combined with some coconut methyl esters to create blends for B5, B15, and B25 biodiesel. Each fuel mixture's physical characteristics, including density at 15 °C, kinematic viscosity at 40 °C, surface tension at 15 °C, and gross calorific value, were tested on a sample. Table 2.1 lists the volume and characteristics of diesel, CME, and their blends (B5, B15, and B25) (Malik et al., 2017).

Table 2.1 : The Fuel Properties of Conventional Diesel fuel and Blends of Coconut Metyl Ester (Malik et al., 2017)

Properties	**Standard**	**Unit**	**Fuels**				
			CDF	B5	B15	B25	B100
CME Volume		L	0	9.5	1.5	2.5	-
Diesel Volume		L	10	9.5	8.5	7.5	-
Density at 15°C	ASTM D941	kg/m^3	830.1	831.5	834.3	837.1	858.2
Kinematic Viscosity at 40°C	ASTM D445	mm^2/s	3.5018	3.4678	3.36	3.2594	2.8396
Surface Tension at 15°C	ASTM D971	N/m	0.0295	0.0296	0.0296	0.0297	0.0305
Gross Calorific Value	ASTM D240	kJ/kg	45,290	44,734	43,891	43,136	37,654

In Table 2.2, the chemical characterization of biodiesel is conducted using specific national standards. These standards include NMX-F-101-SCFI-2012 for the acidity index (AI), NMX-F-174-SCFI-2014 for the saponification index (SI), NMX-F-152-SCFI-2011 for the iodine index (II), and NMX-F-074-SCFI-2011 for the refraction index. The acidity index (AI) is an essential parameter as it indicates the presence of oxidation products and corrosive Free Fatty Acids (FFAs) in the biodiesel. On the other hand, the saponification index (SI) is

inversely proportional to the molecular weight of the oil and provides valuable information about the length of the fatty acid chains in the biodiesel (Opoku-Boahen et al., 2012).

The iodine index (II) is another crucial measurement used to assess the level of unsaturation in the biodiesel, reflecting the number of double bonds present in the oil. The refraction index, influenced by the molecular weight, degree of saturation, length of the fatty acid chain, and degree of conjugation, also plays a role in characterizing the biodiesel (Opoku-Boahen et al., 2012). Overall, the acidity and saponification indices are particularly important for determining the typical molecular weight of fatty acids present in the biodiesel, providing essential insights into its chemical properties.

Table 2.2 : Physico-chemical Properties of Coconut Oil and Coconut Biodiesel. (Lugo-Méndez et al., 2021)

Properties	This work		Bello et al., 2016,		Nakpong et al., 2010,		Chinnamma et al., 2015,		Lafont et al, 2015,		Chen et al., 2012,		Eevera et al., 2009,	Sajjadi et al., 2016,		Limits	
	AC	MEC	AC	MEC	AC	MEC	AC	MEC	AC	MEC	AC	MEC	MEC	AC	MEC		
ρ(g/cm3) at 15°C	0.92	0.86	0.93	0.87	0.92	0.88	0.92	0.88	0.91	0.87	0.93	0.87	0.87	0.92	0.87	0.86-0.9	EN14214
μ(cSt) at 40°C	24.34	2.35	27.23	2.83	28.05	2.94		3.65	28.80	2.80	27.81	2.69	3.47	27.00	3.30	1.9-6.0	D6751
IR	1.46	1.43					1.45						1.43				EN14214
AI (mg KOH/g)	2.23	0.21	2.10	0.18	25.50	0.29		0.24	2.22	0.19	0.07	0.15	0.10	2.10	0.18	> 0.5	D6751
IS (mg KOH/g)	244.19	187.23	190.00	93.00			249.40		155.40	151.20			259.00				
II (gI2/100g)	7.14	42.10	10.00	8.00		30.00	7.70		8.10	10.12	8.83	8.80	9.00	10.00	13.25	≤120	EN14214
CN (min)	67.00	66.00	52.00	70.00				42.10		63.73		60.00	65.34	5.00	64.65	≥47	D6751
HHV (kJ/kg)	37,634	38,329	37,000	36,100		38,100							38,676	37,806	38,200	≥35,000	EN14213
CP (°C)		5.60	0.30	-3.00										10.15	-1.60	-3 - 12	D2500
CFPP (°C)		-2.00	-12.00	-5.00				<-9						5.00	-3.60	-4 - -9	D6371
PP (°C)		-4.00	-6.00	-12.00				-3.00						-6.00	-8.30	-5 - 10	D2500

Table 2.2 includes the following information: density, kinematic viscosity, IR, AI, SI, II, iodine index, cetane number, HHV, high heating value, cloud point, CFPP, and pour point. The ignition delay time that the fuel experiences once injected into the combustion chamber of a diesel engine is connected to the cetane number, which serves as a gauge for the efficiency of diesel combustion. It is calculated using the correlation CN = 46.3 + 5485/IS 0.225II, in accordance with ASTM D613.

2.5 Catalyst Application

Both homogeneous and heterogeneous catalysis are capable of completing transesterification or alcoholysis. In general, homogeneous catalyst processes go more quickly and with less loading than those heterogeneous catalysts. The complicated and frequently unprofitable separation process required to remove homogeneous catalysts from the media makes it difficult or impossible to reuse them. In addition, many washing processes connected with the product's catalyst removal necessitate water use, frequently deionized, and the large production of effluent (Fattah et al., 2020).

Contrarily, because heterogeneous catalysts exist in a distinct phase from the reaction system, the catalyst can be removed at different points during the reaction. These do not require extensive washing procedures before usage. Additionally, because there are significantly fewer dissolved ions than in homogeneous catalysis, high-purity glycerine can be produced, enabling further use in industrial processes. Over the past ten years, transesterification utilizing heterogeneous catalysts has drawn more interest due to the above benefits (Ling et al., 2019). The use of these catalysts is hindered by the partial leaching of the active sites, deterioration of the catalyst microstructure, and organic deposition from the

reaction mixture (Zhang et al., 2020). As a result, creating active, reusable heterogeneous catalysts takes a lot of work to manufacture biodiesel.

In study done by Esmaeili and Foroutan, (2018), goat tallow is trans-esterified to make biodiesel in the presence of homogeneous catalysts like KOH and NaOH. The effects of some variables, including temperature, reaction duration, the ratio of methanol to oil, and the concentration of a catalyst, have been studied for this purpose. The results demonstrated that NaOH and KOH were used to produce the highest biodiesel yields (96 and 98%), and ideal conditions were identified. Additionally, biodiesel was blended with diesel at various ratios (B5-B100) to improve some of its qualities, and its attributes, including flash point, cloud point, pour point, viscosity, and density, were measured. It was discovered that the produced biodiesel's qualities are within the norm and that it can be utilized as a biofuel (Esmaeili & Foroutan, 2018).

Fattah et al. (2020); said one of the potential alternative energy sources is biodiesel, which can be produced using a variety of procedures from low-quality, renewable sources. In the presence of a sufficient catalyst, one of the reactions is alcoholics or transesterification. Both homogeneous and heterogeneous catalysts are possible. The study examines the numerous catalysts used to produce biodiesel, provides the most recent research on different types of catalysts, analyses their applicability, and discusses associated difficulties with the transesterification process. Numerous studies on the generation of biodiesel utilizing homogeneous and heterogeneous catalysis have been conducted, and new heterogeneous catalysts are constantly being looked into (Fattah et al., 2020).

In the conducted study, the high heating value (HHV) of the produced biodiesel was measured using an IKA model C2000 calorimeter, adhering to the ASTM D240 standard.

The experimental procedure involved several steps to ensure accurate results. First, 0.5 grams of each biodiesel sample were carefully weighed using an analytical balance with a measurement range of 0 to 600 grams and an accuracy of 0.1 grams. These weighed samples were then placed in individual metal vessels, which would serve as the ignition point during the calorimetric process. A wick was inserted into the calorimetric pump and firmly fastened to the support of each metal vessel containing the biodiesel sample. The next step involved entering the weight of each sample into the user interface of the IKA C2000 calorimeter. To calculate the high heating value (HHV) of the biodiesel samples, the researchers selected the Dynamic 25 method on the calorimeter. By meticulously following these steps and using the specified equipment and standard, the study successfully determined the high heating value of the produced biodiesel, contributing valuable insights to the understanding of its energy content and potential applications (Lugo-Méndez et al., 2021).

In general, homogeneous catalysts convert single-origin feedstocks that are low in free fatty acids (FFA) and contain water into biodiesel (Silitonga et al., 2013). On the other hand, heterogeneous catalysts offer greater activity, a more comprehensive range of selectivity, good FFA, and water adaptability(Fattah et al., 2014). These characteristics are governed by the number and potency of active acids or base catalyst (Tan et al., 2019). By making the appropriate modifications, some heterogeneous catalysts, like those on zirconia and zeolite, can be employed as both base and acidic catalysts. To develop a sustainable replacement for current homogeneous catalysts used in biodiesel manufacturing, heterogeneous catalysts made from waste and biocatalysts are crucial. Nanocatalysts have received interest recently due to their excellent catalytic efficiency under benign operating conditions.

This study analyses the current state of the art and prospects for catalytic biodiesel production. It also evaluates the key operational factors that affect biodiesel production and technological advancements for the process's sustainable adoption.

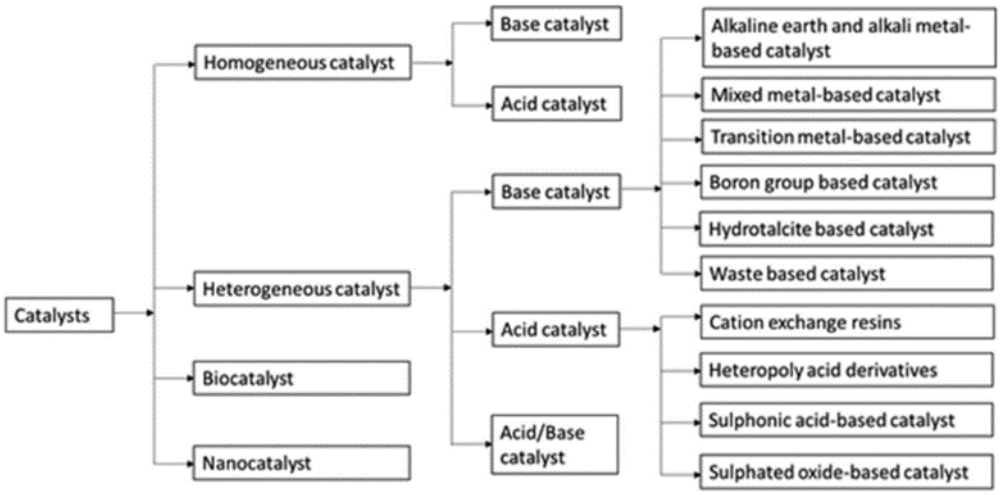

Figure 2.3 : Different Catalyst Used Biodiesel Production (Fattah et al., 2020)

2.6 Transesterification

The traditional method for producing biodiesel is transesterification or alcoholysis. The process involves reacting triglycerides with alcohols (usually methanol) in the presence of a catalyst to speed up the reaction. The process's final product is commonly called fatty acid methyl esters (FAME) (Mahlia et al., 2020).

Transesterification is the process of converting triglycerides into diglycerides, monoglycerides, and finally, glycerin (also known as glycerol) in a series of rapid, reversible, and catalyzed processes (Ong et al., 2019). Typically, alkali catalysts are used in a single-step transesterification reaction to make biodiesel. However, depending on the amount of FFA and water present, a two-step reaction may be necessary. The transesterification process is preceded by acid-catalyzed alcoholysis, also known as esterification (Ashraful et al., 2014).

Figure 2.4 depicts the schematic diagram for the one- and two-step biodiesel synthesis processes.

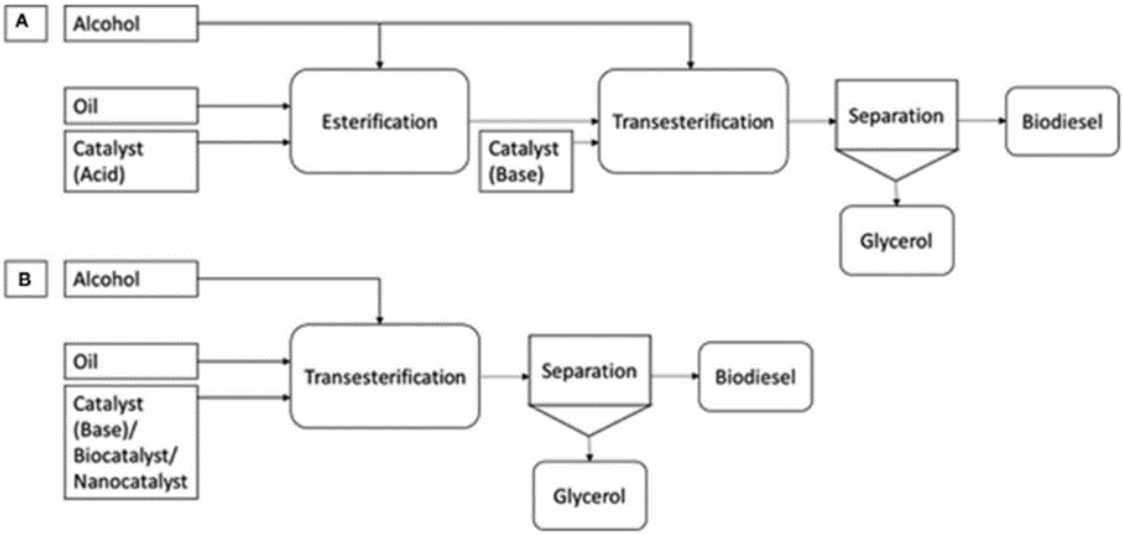

Figure 2.4 : Transesterification Process. Process A : Two-step process. Process B : One step Process. (Fattah et al., 2014; Mofijur et al., 2014)

2.6.1 One-Step Transesterification

The major components of this one-step transesterification procedure were catalyst, methanol, and coconut oil. Catalyst loading, reaction time, and catalyst concentration were the parameters used for this investigation. The 250 mL three-necked round-bottom flask equipped with a reflux condenser, heating mantle with a stirrer, and thermometer has been used to conduct the reaction procedure. First, the catalyst was activated by dispersing it in 120 g of methanol at 50 for 20 minutes while maintaining a steady stirring speed. Following catalyst activation, 10 g of coconut oil was added to the three-necked round-bottom flask after being preheated for 20 minutes. The mixture was refluxed at a reaction temperature of 65 while continuously stirring for varied reaction times (Farooq & Ramli, 2015).

The reaction mixture was filtered through filter paper to remove the solid catalyst and other remnants once the transesterification reaction had finished. The mixture was put

into a separatory funnel and allowed overnight to separate the biodiesel from the glycerol component. The top layer is the obtained biodiesel, and the bottom layer is glycerol. The excess methanol was removed from the biodiesel using a distillation procedure to purify it (Mahesh et al., 2015). The refined biodiesel was kept in a sealed vial. In order to ascertain the methyl ester composition, the quality of biodiesel products was examined utilising the Agilent Technologies 7890B GC system-5977A MSD (GC-MS) and Perkin Elmer Spectrum TM 100 FTIR spectroscopy.

2.6.2 Two Step Transesterification

In the study conducted by Kumar et al. (2010), produced coconut biodiesel through acid esterification and base transesterification methods. For acid esterification, they used 0.35 weight percent of sulphuric acid catalyst based on 10 grams of coconut oil. The reaction mixture of catalyst, methanol (120 g), and coconut oil (10 g) was heated and stirred at 65 °C for different reaction times. After completion, the mixture was transferred to a separatory funnel, and the bottom phase was collected and purified using a rotator evaporator.

For base transesterification, they activated the potassium hydroxide (KOH) catalyst with methanol and used a constant methanol-to-oil ratio of 12:1. The KOH catalyst was 3 weight percent based on 5 grams of oil. The reaction was again heated and stirred at 65 °C for varying periods (3, 4, and 5 hours). Afterward, the mixture was left in the separatory funnel overnight to separate glycerol and FAME (fatty acid methyl esters). The top phase was extracted and purified through distillation.

To characterize the purified biodiesel, they used Agilent Technologies 7890B GC system-5977A MSD (GC-MS) and Perkin Elmer Spectrum TM 100 FTIR spectroscopy. The

yield of biodiesel was calculated using Equation 1: Yield (%) = weight of the produced biodiesel / 100% of the oil's weight. (Kumar et al., 2010)

Awolu and Layokun, (2013) studies examined the optimization of neem oil (*Azadirachta indica*) transesterification for the manufacture of biodiesel and assessed the properties of the neem oil biodiesel. This was done in an effort to determine the potential for production and viability. Transesterification was carried out in two steps to produce biodiesel. The first procedure took place in 1 hour at 50 °C with a 0.60 weight-to-weight methanol-to-oil ratio and 1% weight-to-weight H_2SO_4 as an acid catalyst. The product from the first stage was base (NaOH) transesterified utilizing the parameters laid out in the optimization design in the second phase.

In the second step of the composite design optimization process, the main variables were temperature (ranging from 45 °C to 65 °C), catalyst quantity (0.45% to 1.45% w/w), reaction duration (45 to 65 minutes), and the methanol/oil molar ratio (ranging from 1.5 to 7.5). The physicochemical characteristics of the neem biodiesel were determined using standard techniques, and gas chromatography was utilized to analyze the fatty acid composition. The optimized biodiesel yield of 89.69% was achieved at a reaction period of 65 minutes, a catalyst weight of 0.95 g, a temperature of 55 °C, and a methanol/oil molar ratio of 4.5:1. (Awolu & Layokun, 2013).

0.05% moisture content, 0.9 specific gravity at 25 °C, 5.5 mm2/S kinematic viscosity, 207 mg KOH/g, 70.7 g I2/100 g iodine value, 55.31 cetane number, 39.85 MJ/Kg calorific value, 4 pour point, 8 cloud point, and 110 flash point are the values for the physicochemical parameters. These criteria are in line with those set forth by the American Society for Testing and Materials, among others (ASTM). Based on its physicochemical characteristics and the

engine test, it can be said that neem biodiesel demonstrated a general compliance with accepted requirements. These, together with its high output, attested to the viability and effectiveness of the two-step transesterification process used to produce neem biodiesel (Awolu & Layokun, 2013).

Shohaimi and Marodzi, (2018) studied that given that fossil fuels are natural and non-renewable resources, the rising demand for them raises serious concerns. Numerous experiments have been conducted on biodiesel produced from renewable sources, such as used cooking oil. Transesterification reaction is the name given to the one-step (esterification) and two-step (esterification-transesterification) reactions required to convert used cooking oil into biodiesel. Investigations were done on the CaO/Al_2O_3 catalyst's performance. Reaction time and catalyst loading were the variables under investigation. In this investigation, it was discovered that the two-step transesterification reaction produced the maximum yield (30.91%), under the ideal conditions of 3 weight percent CaO/Al_2O_3 catalyst, a 12:1 methanol to oil ratio, and a reaction temperature of 65 °C for three hours.

The esterification reaction effectively reduces the free fatty acid (FFA) concentration in the feedstock, aiming to achieve a high biodiesel yield with an acid value below 1 mg KOH/g of oil. Through a two-step transesterification reaction, the free fatty acid has been successfully converted into methyl ester. This transformation was supported by GC-MS data, which identified six different species of methyl ester in the final product. (Shohaimi & Marodzi, 2018).

As a result, two-step reaction processes yield more FAME than one-step ones. The transesterification reaction conditions of 3 hours of reaction time, a 12:1 methanol to oil ratio, a temperature of 65 °C, and the best CaO/Al_2O_3 loading, 3 wt%, resulted in a 30.91% FAME

yield for a two-step procedure. Despite the low yield, GCMS and FTIR were used to confirm that the sample's FFA content had been changed into FAME. Despite the fact that there are minute changes in the FTIR spectra because the biodiesel and WCO are chemically similar, the GCMS analysis was successful since there were few common groups of methyl esters (Shohaimi & Marodzi, 2018).

Kasirajan (2021) in his study performing two-step transesterification procedures to produce biodiesel from *Chrysophyllum albidum* seed, a non-edible source. The superheated extractor used a mixed solvent to extract the lipids, and gas chromatography was used to identify the compositions of the fatty acids (GC). Using a homogeneous H_2SO_4 catalyst, *Chrysophyllum albidum* seed oil first experiences an esterification reaction. The effects of transesterification parameter variations on reaction temperature, catalyst loading, methanol-oil molar ratio, reaction time, and stirring rate were investigated.

The maximum oil to biodiesel conversion was 99.2 weight percent at the ideal conditions of 1:9 oil to methanol molar ratio, 1 weight percent of KOH, 500 rpm of mixing intensity, and 40 minutes of reaction time at 65 °C. The 1H-NMR Spectroscopy was used to analyse and confirm the conversion of oil to biodiesel, and the physical-chemical properties were examined and compared to ASTM requirements. Our experimental research suggests that a two-step esterification and transesterification procedure is extremely appropriate for producing biodiesel from *Chrysophyllum albidum* (Kasirajan, 2021).

2.7 Direct Use and Blending

The use of vegetable oils directly as fuel for diesel engines has been explored since the early 1900s due to several advantages they offer over traditional diesel fuel. Firstly, vegetable oils are in liquid form, which makes them relatively easier to handle and transport

compared to other alternatives. Secondly, their heat content is approximately 80% that of diesel fuel, making them a viable option for energy production. Moreover, vegetable oils are readily available, as they can be derived from various plant sources, and they are renewable, which aligns with the increasing global focus on sustainable energy solutions. (Abbaszaadeh et al., 2012).

However, despite these advantages, vegetable oils also come with certain drawbacks that hinder their direct use as diesel engine fuel. One notable issue is their higher viscosity, which can lead to poor atomization and combustion characteristics, resulting in engine performance and efficiency challenges. Additionally, vegetable oils tend to have reduced volatility compared to diesel fuel, affecting their ability to vaporize and ignite efficiently in the engine. Furthermore, the presence of unsaturated hydrocarbon chains in vegetable oils makes them more reactive, leading to higher rates of oxidation and polymerization during combustion. This can result in increased engine deposits and potential engine wear over time (Abbaszaadeh et al., 2012).

To address these inherent issues and make vegetable oils more suitable as diesel engine fuel, researchers often opt to blend or dilute the crude vegetable oils with traditional diesel fuel. This process helps to regulate the viscosity and improve the overall fuel characteristics, making it easier to use in diesel engines without significant performance drawbacks. By blending or diluting vegetable oils with diesel fuel, the resulting biodiesel or biofuel exhibits better compatibility with diesel engines, enhanced combustion properties, and reduced engine wear. Thus, this approach provides a viable and sustainable solution to utilize vegetable oils as an alternative and greener energy source in diesel engines (Abbaszaadeh et al., 2012).

2.8 Microemulsion

A potential solution to the issue of the crude natural oil's excessive viscosity is micro-emulsification. A microemulsion is described as a spontaneous formation of two ordinarily immiscible liquids, one or more ionic or non-ionic amphiphiles, and a colloidal equilibrium dispersion of optically isotropic fluid microstructures with diameters typically in the range of 1-150 nm. An oil phase, an aqueous phase, and a surfactant are typically the three elements that make up a microemulsion (Abbaszaadeh et al., 2012).

Another study created and tested coconut oil-based hybrid fuel on a PowerTec 170FG 4-stroke, single-cylinder, air-cooled, DI diesel engine. The fuel was a coconut oil-aqueous ethanol microemulsion with butan-1-ol as a surfactant in various compositions. A successful micro-emulsification of coconut oil produced diesel-like fuel with a viscosity that was close to that of diesel, yielding positive test results. With much reduced levels of NO, SO_2, and CO_2 emissions, coconut oil-ethanol microemulsion use improved engine efficiency that is practically on par with diesel. However, due to a lower gross calorific value and incomplete combustion, respectively, hybrid fuel's specific fuel consumption (SFC) and CO emission level were higher than those of diesel (Singh & Singh, 2010).

2.9 Pyrolysis

Vegetable oil could not be used directly as fuel in a diesel engine without modification because it is known to have a problem with high viscosity and density that impacts the fuel atomization in the engine. This issue can be resolved by pyrolysis or thermal cracking, which uses heat to break down hydrocarbons into their most basic structure, either with or without the use of a catalyst. High temperature levels between 250 °C and 350 °C will result in pyrolysis (Koh & Tinia, 2011).

Even though the market for biodiesel is frequently saturated with products made from edible oils, many current studies are concentrating on how to switch from edible to non-edible biodiesel feedstocks. Due to its potential to generate issues in the areas of the environment, social issues, economic issues, and political issues in some nations, biodiesel produced from edible oil sources has come under intense scrutiny. Animal fat waste makes for both economical and environmentally friendly feedstock. This is because its use as a biodiesel feedstock reduced the amount of trash that needed to be dumped in landfills and because it is easily accessible for little to no money (Mašek, 2016).

2.10 Diesel Engine Performance and Exhaust Emission Analysis

Engine test is usually done to evaluate the biodiesel ability to be used in the real or consumer scenario. The parameters commonly studied are brake power, engine power output, specific fuel consumption, and exhaust gas emission. These parameters provide comparative data for the various type of biodiesel, and more often than not, they are dissimilar from one biodiesel feedstock to another (Sakthivel et al., 2018; M. Suresh et al., 2018).

In a study conducted by Suthisripok & Semsamran (2018), TA 14-hp Kubota RT140 DI diesel engine was used to test palm oil biodiesel with a B100 composition for 800 hours of operation at high load and low speed while operating 12 hours daily to aerate a fish pond. The purpose of the experiment was to evaluate the mechanical longevity and dependability of using 100% biodiesel in a small farm diesel engine Suthisripok & Semsamran (2018).

Based on the demographic analysis and ocular inspection, it was discovered that the engine developed wear at the typical rate. It follows that biodiesel B100 can be used as a substitute fuel for a small diesel engine without experiencing significant mechanical durability issues. Several blends of animal fat-based biodiesel (B10, B20, B30, B40, and

B50) were used in an experimental investigation by Shahir et al. (Shahir et al., 2017) to run a turbocharged common rail direct injection (CRDI) engine at a constant speed of 2800 rpm. It was discovered that B30 animal fat biodiesel performed optimally and had superior emission characteristics to diesel. Due to its lower calorific value and higher viscosity, biodiesel with a higher content had a higher break-specific fuel consumption (BSFC) and lowered thermal efficiency. Due to the increased oxygen content in biodiesel, the emissions of CO_2 and NO_x were also enhanced (Shahir et al., 2017).

In other research by Mumtaz et al (200$), up to 20% of coconut oil can be used successfully in CI engines when blended with diesel. Additionally, coconut oil can be turned into biodiesel and used straight in CI engines or combined in any amount with diesel. By utilizing a renewable resource, the potential use of coconut oil in power production promotes the ideas of sustainability and greener manufacturing.

Reddy et al. (2017) researched about the production of jatropha biodiesel catalyzed by CaO catalyst from eggshells and seashells. In the literature, engine power output and brake power were deceased when the biodiesel blending ratio increased. Nevertheless, the SFC of the engine increased along with the biodiesel blending ratio (Reddy et al., 2017a). Islam et al. (2014) also reported a decrease in brake power and engine power output when the castor biodiesel percentage ratio with petrodiesel was increased (Islam et al., 2014). Emiroğlu et al. (2018) reported an increase in SFC with the blending percentage increase of biodiesel from turkey rendering fat. The literature also reported an increase in NO_x emission along with the increase in biodiesel blending percentage (Emiroğlu et al., 2018). On the contrary, Nalgundwar et al. (2016) reported that brake power was increased, while SFC decreased with the increase of biodiesel blending percentage. CO emission was decreased,

while NO_x emission was increased with the increase of biodiesel blending percentage (Nalgundwar et al., 2016).

Sivakumar et al. (2018) studied the effect of aluminum oxide nanoparticles as a catalyst on biodiesel blend's performance, combustion, and emission characteristics. The results showed that SFC and NO_x emission increase when using pongamia methyl ester blended at 25% volume compared to petrodiesel. Nonetheless, CO and HC emissions decreased (Sivakumar et al., 2018) However, Wei et al. (2018) reported a decrease in NO_x emission, while confirming that SFC was increased when the WCO biodiesel blend percentage increased (Wei et al., 2018). Abdalla (2018) compared the emissions of biodiesel blends of B10 to B90 with petrodiesel. The emissions of CO, HC, and NO_x were reported to decrease as the biodiesel blending increased from 10% (B10) to 90% (B90). Petrodiesel recorded the highest emissions compared to all biodiesel blends (Abdalla, 2018).

Suresh et al. (2016) studies shows that a longer ignition delay for diesel results in delayed combustion, which results in reduced cylinder pressure. However, the cylinder pressure for biodiesel blends is slightly lower than that of diesel during the late combustion phase (S. Suresh et al., 2016). This is due to the increased oxygen content in biodiesel and its blends, which ensures complete burning of the fuel. Suresh et al. (2016) discovered that the thermal efficiency of the brakes increased with increasing load for both biodiesel blends and diesel. Break thermal efficiency (BTE) is reduced due to biodiesel's lower viscosity, spray properties, and calorific value (Chinnamma et al., 2015; Suresh et al., 2016). Because higher viscosity reduces atomization, fuel vaporization, and combustion, biodiesel blends have worse thermal efficiency than diesel (Chinnamma et al., 2015; Suresh et al., 2016).

Suresh et al. (2016) recorded the specific fuel consumption decreased with increase in load for both the biodiesel blends and diesel (Mofijur et al., 2014; Suresh et al., 2016). This is due to the fact that biodiesel blends have a lower calorific value than diesel fuel, requiring more biodiesel fuel to maintain a constant power output (Yilmaz et al., 2014). The decrease in SFC as engine load increases can be due to insignificant heat losses at higher engine loads. Can et al. (2014) reported the drop in SFC with increasing load could be explained by the fact that the percentage increase in fuel required to run the engine was less than the percentage increase in brake power (Can, 2014; Suresh et al., 2016).

Tan et al. (2015) said the amount of fuel injected in each cycle increases as the load increases, increasing NOx emissions (Tan et al., 2015). This raises the temperature of the cycle. NO_x emissions are affected by temperature and combustion time (Tan et al., 2015). Biodiesel is an oxidized fuel, it produced more NO_x. As a result, the chain reaction between the oxygen in biodiesel and the nitrogen in air results in greater NO_x emissions (Kumar et al., 2015).

Suresh et al. (2016) biodiesel blends studies reported 39.5% reduction in CO with increase in the volumetric percentage of the biodiesel in the blend (Suresh et al., 2016). The combustion temperature and oxygen content both influence CO formation (Can, 2014). When the load is increased, the CO emission for diesel increases dramatically due to a lack of oxygen in the surrounding area (Mofijur et al., 2014). Because biodiesel is an oxidized fuel (it contains oxygen), it can engage in more chemical reactions in biodiesel blends (Yilmaz et al., 2014). As a result of better combustion, CO emissions for biodiesel were lower than those for diesel during maximum loading as the biodiesel blend increased (Kumar et al., 2015; Suresh et al., 2016).

Damanik et al. (2019) shows studies on performance and emission exhaust of a diesel engine fuelled with *Calophyllum inophyllum*-palm biodiesel. Biodiesel blended fuels offer 16%-21% greater BSFC than diesel fuel on average (Mofijur et al., 2014; Mofijur et al., 2013; Öztürk, 2015). Öztürk et al. (2015) studied a combination of canola oil-hazelnut soap stock biodiesel-diesel and discovered that the BSFC of the blend fuel is greater than that of diesel fuel. That result was generated by the combined effects of the fuel's density, KV, and HV (Mofijur et al., 2014; Öztürk, 2015). Biodiesel is injected in volume during the suction stroke, allowing more fuel to enter the cylinder (Syed et al., 2017). As a result, because biodiesel has a lower HV than diesel, more fuel is required to create the same power. Biodiesel has a lower HV than diesel, more fuel is required to create the same power. The average BSFC for the blends was highest for *Calophyllym inophyllum* Methyl ester (CIME) 10 (2.58 Ltr/kWhr) and lowest for CIME5 (2.21 Ltr/kWhr), which can be attributed to the heating value of the CIME10 blends. CIME10 fuel sample has a little greater heating value (43.9 MJ/kg) than CPME5 (43.1 MJ/kg).

Damanik et al. (2019) also reported that the BTEs of all fuel samples utilised in their investigation rise with speed, with diesel fuel having the highest BTE when compared to blended fuels. This is explained by diesel fuel's higher heating value and lower BSFC (Rahman et al., 2017). Diesel fuel has the highest BTE, followed by CPME5, CIME5, CPME10, and CIME10 fuels. When compared to diesel fuel, blended fuel reduces BTE by 1.25%-22% on average. Diesel fuel has a lower viscosity and a higher heating value, which promotes fuel atomization and hence increases BTEs (Sharma et al., 2012).

The relationship between engine speed and NO_x emissions is evident, as higher engine speeds typically lead to increased NO_x emissions. It is also evident from the literature

that biodiesel blended fuels tend to emit higher NO_x compared to pure diesel fuel. A study comparing B7 and B100 biodiesel blends observed a similar trend (Özçelik et al., 2015). On average, diesel fuel exhibits NO_x levels of 112 ppm, which can be 1.5% to 29% greater than those emitted by blended biodiesel fuels. This difference in NO_x emissions can be attributed to the higher intrinsic oxygen content in biodiesel compared to diesel fuel. Oxygenated fuels, including biodiesel blends, are known to produce higher NO_x levels, as reported in studies involving oxygenated gasoline blends (Mofijur et al., 2013).

Additionally, the higher kinematic viscosity (KV) of biodiesel fuels leads to larger droplets and shorter ignition delays, which can influence NO_x emissions (Kalam et al., 2011). The concentration of unsaturated fatty acids in biodiesels is another factor contributing to increased NO_x emissions, as it generates a higher adiabatic flame temperature compared to diesel fuel (Özçelik et al., 2015). Furthermore, it's important to note that biodiesel fuels might experience heating loss during the combustion process, which can further impact their NO_x emissions. The presence of impurities or incomplete combustion of biodiesel can result in heating losses, affecting the overall combustion efficiency and the emissions profile of the fuel.

Overall, the higher NO_x emissions observed in biodiesel blended fuels compared to pure diesel fuel can be attributed to the unique chemical properties and combustion characteristics of biodiesel, such as its oxygen content, kinematic viscosity, and fatty acid composition. These factors play a significant role in influencing the emission profiles of biodiesel blends, particularly with respect to NO_x emissions.

The study conducted by Dinesha & Mohanan et al. (2018), show that CO emissions from biodiesel blends are lower than those from diesel fuel. Biodiesel fuel reduces CO

emissions by 5% to 15% on average when compared to diesel fuel. The rationale is that biodiesels have a larger oxygen concentration, which results in cleaner, better combustion, CO is produced as a result of incomplete combustion of the fuel due to a lack of oxygen or a low gas temperature. As previously stated, biodiesel fuel contains 12% more oxygen than diesel fuel, allowing more carbon molecules to be burned entirely (Mofijur et al., 2013).

It was discovered that the average HC emissions of blends were lower than those of diesel. Biodiesel blended gasoline clearly reduces HC emissions by 13%-22% compared to diesel fuel. Because of the presence of extra oxygen atoms in biodiesel, HC emissions can be minimized by improving combustion quality in biodiesel diesel blends (Man et al., 2016). Mofijur et al. (2014) indicated that the decreased hydrocarbon emissions of moringa biodiesel-diesel are caused by the increased oxygen content of biodiesel fuel compared to diesel fuel. Based on Figure 2.5, it shows that as engine speeds increase, HC emission decreases. (Mofijur et al., 2014). Kegl (2011) found that when engines run at lower speeds, both biodiesel and diesel fuel release higher HC emissions (Kegl, 2011).

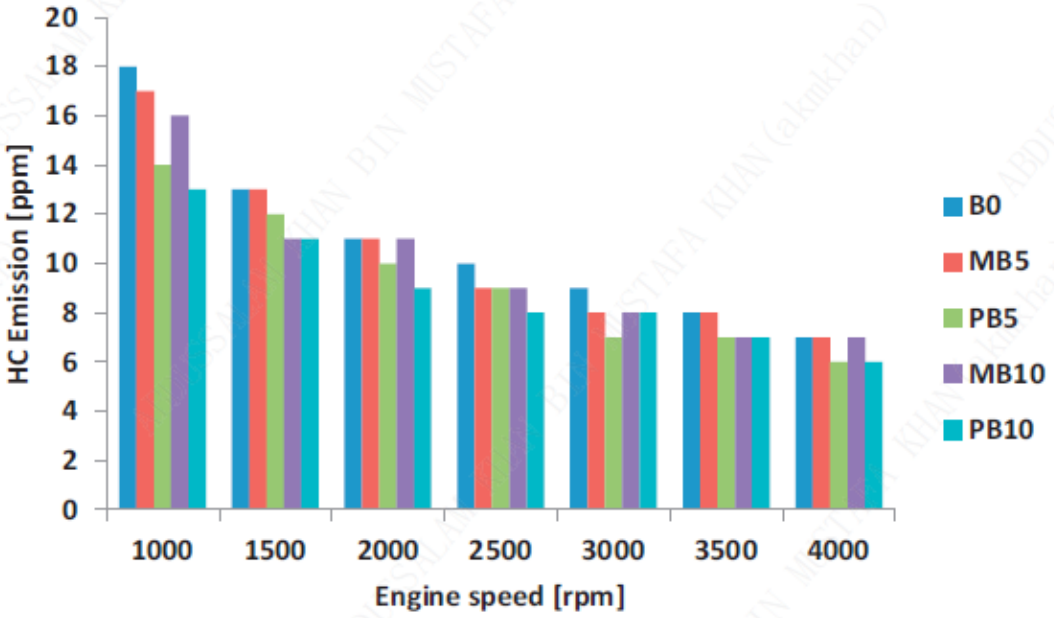

Figure 2.5 : Graph of HC Emission versus Engine Speed (Mofijur et al., 2014)

In conclusion, the literature review provides valuable insights into the diverse and dynamic landscape of biodiesel production and application. The studies demonstrate the feasibility of biodiesel as a sustainable alternative to conventional diesel fuel, emphasizing its potential to reduce greenhouse gas emissions, dependence on finite fossil fuel resources, and waste generation. The various biodiesel production methods, such as transesterification (acid and base-catalyzed), microemulsion, and pyrolysis, offer flexibility and adaptability to utilize a wide range of feedstock sources, including both edible and non-edible oils and fats. Researchers have made significant strides in optimizing transesterification conditions to achieve higher yields and improve the physicochemical characteristics of the produced biodiesel, aligning with international standards.

Moreover, the engine performance and exhaust emission analysis of biodiesel blends have shed light on their impact on diesel engines. While biodiesel blends generally reduce emissions of carbon monoxide (CO) and hydrocarbons (HC) due to improved combustion

quality, they tend to increase nitrogen oxides (NOx) emissions attributed to the higher oxygen content in biodiesel. Blending biodiesel with conventional diesel or microemulsification has emerged as effective strategies to mitigate the challenges associated with biodiesel's higher viscosity and combustion characteristics, enhancing its compatibility with diesel engines.

The studies' emphasis on non-edible feedstocks, such as animal fat waste and non-edible plant oils, addresses concerns about food competition and waste utilization, further enhancing the environmental and sustainability aspects of biodiesel production. As research progresses, biodiesel continues to demonstrate its potential as a greener, renewable, and economically viable energy solution, paving the way for a more environmentally conscious and sustainable energy future. Nonetheless, ongoing research is essential to address remaining challenges, including feedstock availability, cost-effectiveness, and the comprehensive understanding of biodiesel's impact on engine performance and exhaust emissions to fully harness its benefits and promote widespread adoption in the energy sector.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Coconut biodiesel production begins with crude coconut oil collection and preparation. Filtered crude coconut oil then was tested for its Free Fatty Acid (FFA) content. After FFA analysis was performed, two steps transesterifaction of crude coconut oil were conducted using homogenous catalyst. Produced CB was than characterized to understand the physicochemical properties. After characterization of CB physicochemical properties, it was then blended with petrodiesel. The CB blends were then tested on a stationary diesel engine to evaluate the mechanical performance and exhaust emissions. Figure 3.1 shown below is the flow of methodology.

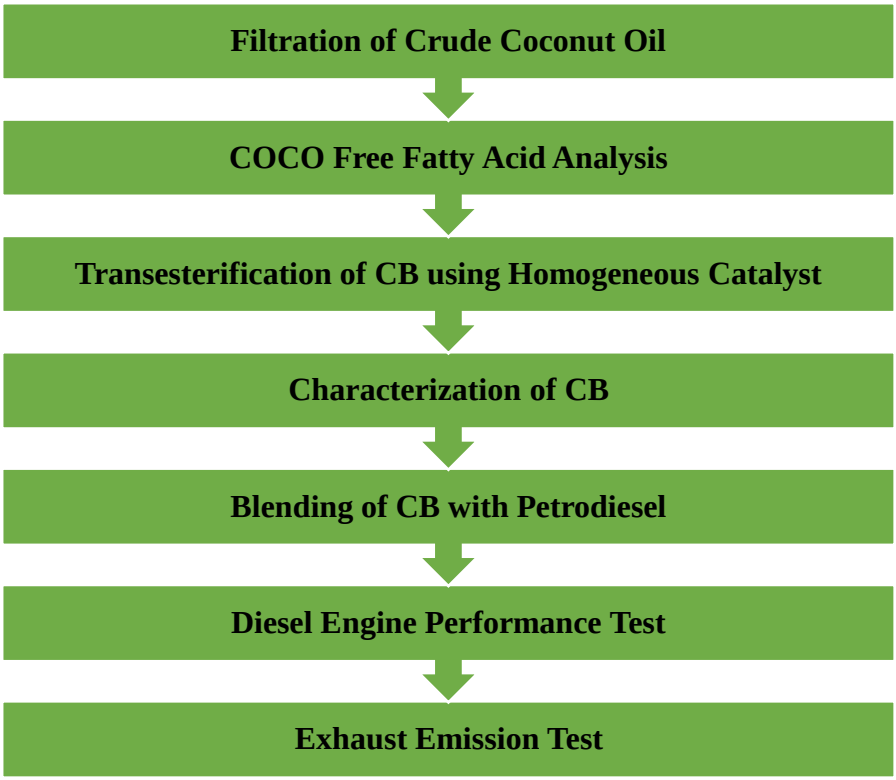

Figure 3.1 : Chronology of Biodiesel Production and Analysis

3.2 Laboratory

Production of Coconut Biodiesel was done in the Energy Laboratory and Physical Metallurgy Laboratory in the Faculty of Engineering, UNIMAS. Chemical properties determination was done in the Chemical Laboratory and engine testing was carried out at Diesel Engine Laboratory in the Faculty of Engineering, UNIMAS.

3.3 Raw Materials

Crude Coconut Oil (COCO) used in this study was purchased from Kampung Buntal, Kuching, Sarawak, Malaysia. COCO purchased was 3.5 litre. Only 2.87 litre crude coconut oil used up to produce biodiesel.

COCO could not be directly used as substitute of conventional diesel because it does not meet the standard or specification of conventional diesel. To have comparable or better properties with diesel fuel, COCO needs to be converted into coconut methyl ester. There are specifically four methods to produce biodiesel. These are blending or dilution, emulsification, pyrolysis and transesterification. Among the methods developed, transesterification using acid/alkali as catalyst gives high biodiesel yield in shorter duration at much lower cost (Altepkin et al., 2010). Since COCO has high FFA value and high water content, it is advisable to carry out the two-step transesterification because of the FFA percentage is more than 4% (Lugo-Méndez et al., 2021; Reddy et al., 2015).

The transesterification is performed with the usage of the homogeneous acid catalyst and base catalyst. The homogeneous acid catalyst chosen was sulphuric acid which lessen the FFA content and the base catalyst chosen was sodium hydroxide. The test commenced with measuring the FFA content of COCO through titration. If the FFA content exceed 4%, then the acid pre-treatment is performed. After that, the second step base catalyst

transesterification is carried out to produce biodiesel. The optimum parameters and types of devices used which contributes to maximum yield of biodiesel are analysed.

Hence, COCO needs to go through two steps transesterification to produce coconut methyl ester. During the transesterification process, the most effective methanol to oil ratio, catalyst concentration, response time, and response temperature are being analyzed to determine the key reaction parameters which contribute to the highest yield and lowest cost of producing CB. Once coconut methyl ester is produced, the coconut methyl ester and COCO chemical structure are analysed. Properties comparison to be carried out are chemical composition analysis via calorific value analysis using bomb calorimeter, density analysis via density meter, and flash point analysis through flash point tester.

3.4 Crude Coconut Oil Filtration

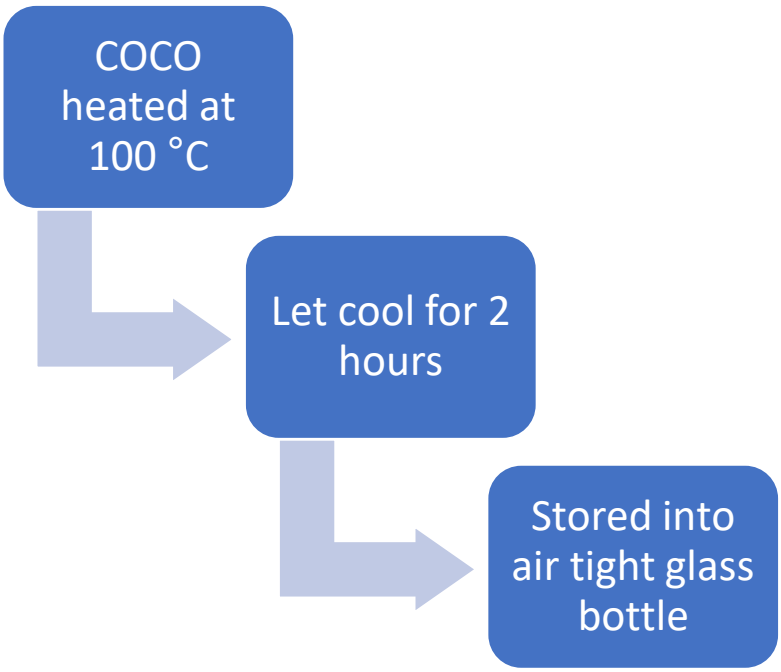

Figure 3.2 : Crude Coconut Oil Filtration Steps

The COCO filtration method was adapted from Atadashi et al. (2011); Samart et al. (2013) and Aburto et al. (2019). Crude coconut oil bought was place in 1 litre beaker and heated on a hot plate (Thermo Scientific SP131320-33) at 100°C for an hour. Crude coconut oil was then let cool for 2 hours and filtered through a filter paper to remove any solid particle. Filtered crude coconut was then stored an in 1 litre air tight bottle to be used for FFA analysis experiment.

3.5 Free Fatty Acid Analysis

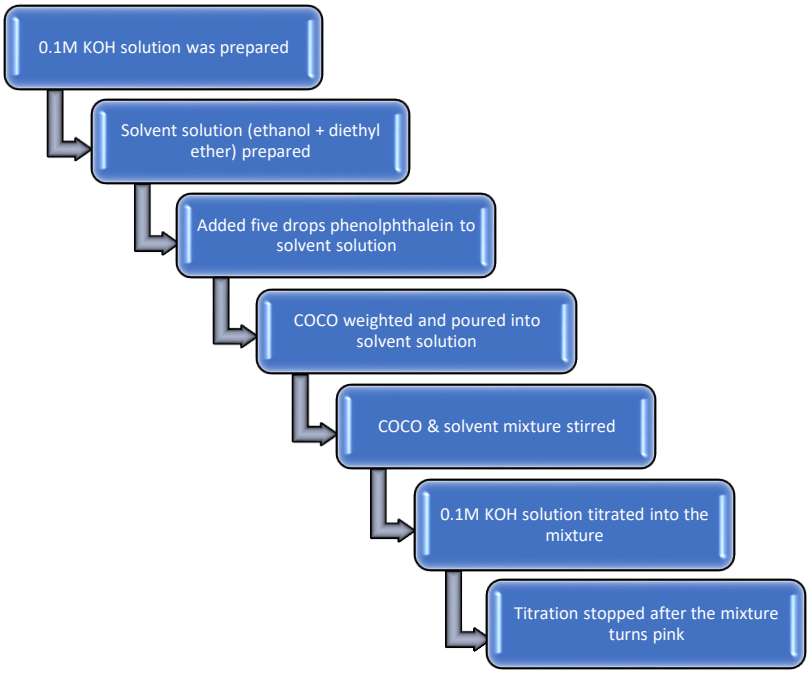

Figure 3.3 : FFA Experimental Steps

Crude coconut oil FFA content was determined through titration with 0.1M KOH standard solution. 30 ml of 0.1M KOH solution was prepared and filled inside a burette. A solvent solution of ethanol with 95% concentration and diethyl ether was prepared with a ratio of 1:1 v/v inside a conical flask. Five drops of phenolphthalein were added into the solvent solution as an indicator. Crude coconut oil was weighted and poured into the conical flask containing solvent solution. The solvent and COCO mixture were stirred with a

magnetic stirrer (Thermo Scientific SP131320-33) and the 0.1M KOH solution was titrated into the mixture. The titration was stopped when the color of the solvent and COCO mixture turned from clear to pink for more than 10 seconds as shown in Figure 3.3. The acid value of the crude coconut oil is calculated using the volume of 0.1M KOH solution needed for titration and the weight of the oil sample as shown in Equation 3.1. The acid value represents the number of milligrams of KOH required to neutralize the free fatty acids present in one gram of oil. This value is a critical parameter in determining the quality and stability of the oil.

$$\text{Acid value (mg KOH/g)} = \frac{MW_{KOH} M_{KOH} V_{KOH}}{W_{sample}} \quad \text{(ASTM, 2014)} \qquad \text{Equation 3.1}$$

where: MW_{KOH} = Molar mass of KOH in g/mol

M_{KOH} = Molarity of KOH solution in mol/L

V_{KOH} = Volume of KOH solution needed for titration in mL

W_{sample} = Weight of coconut crude oil in grams

The experiment was repeated for at least two more times and the average acid value was calculated and reported in term of mg KOH/g.

Table 3.1 : Specification of Chemicals

Name of chemicals	Chemical formula	Molar Mass, g/mol	Density, g/mL	Boiling Point,℃	Brand
Methanol	CH_3OH	32.04	0.7918	65.0	MERCK
Potassium Hydroxide	KOH	56.11	2.044	1327.0	MERCK

Table 3.1 continue

Ethanol	C_2H_5OH	46.07	0.789	78.0	MERCK
Sulphuric Acid	H_2SO_4	98.079	1.84	337.0	RQM
Di-ethyl Ether	$C_4H_{10}O$	74.12	0.7134	34.6	Hmbg
Phenolphthalein	$C_{20}H_{14}O_4$	318.32	1.277	N/A	Hmbg

3.6 Transesterification

3.6.1 Acid Pre-treatment (Esterfication)

Crude coconut oil esterification process was performed by using experimental matrix parameters listed in Table 3.2 and Table 3.3 below :

Table 3.2 : Esterification Experimental Matrix Process Parameters (Mohiddin, 2018)

Fixed Variables	Variable tested: Catalyst to Oil Ratio (v/v)						Observation
	CTO1	CTO2	CTO3	CTO4	CTO5	CTO6	Optimum CTO, **CTO***
MTO, RT1, RT2	CTO1, MTO, RT1, RT2	CTO2, MTO, RT1, RT2	CTO3, MTO, RT1, RT2	CTO4, MTO, RT1, RT2	CTO5, MTO, RT1, RT2	CTO6, MTO, RT1, RT2	
Fixed Variables	Variable tested: Methanol to Oil Ratio (v/v)						Observation
	MTO1	MTO2	MTO3	MTO4	MTO5		Optimum MTO, **MTO***
CTO*, RT1, RT2	MTO1, CTO*, RT1, RT2	MTO2, CTO*, RT1, RT2	MTO31, CTO*, RT1, RT2	MTO4, CTO*, RT1, RT2	MTO5, CTO*, RT1, RT2		
Fixed Variables	Variable tested: Reaction Time (hours)						Observation
	RT11	RT12	RT13	RT14			Optimum RT1, **RT1***

Table 3.2 continue

CTO*, MTO*, RT2	RT11, CTO*, MTO*, RT2	RT12, CTO*, MTO*, RT2	RT13, CTO*, MTO*, RT2	RT14, CTO*, MTO*, RT2		
Fixed Variables	Variable tested: Reaction Temperature (°C)					Observation
	RT21	RT22	RT23	RT24	RT25	
CTO*, MTO*, RT1*	RT21, CTO*, MTO*, RT1*	RT22, CTO*, MTO*, RT1*	RT23, CTO*, MTO*, RT1*	RT24, CTO*, MTO*, RT1*	RT25, CTO*, MTO*, RT1*	Optimum RT2, **RT2***

Table 3.3 : Esterification Reaction Condition Matrix (Khan et al., 2021)

CTO (v/v)						MTO (v/v)				
1	2	3	4	5	6	1	2	3	4	5
1:0.01	1:0.02	1:0.03	1:0.04	1:0.05	1:0.06	1:0.2	1:0.4	1:0.6	1:0.8	1:1
RT1						RT2				
1	2	3	4			1	2	3	4	5
1hr	2hrs	3hrs	4hrs			45°C	50°C	55°C	60°C	65°C

Process flow of esterification are shown in Figure 3.4 below :

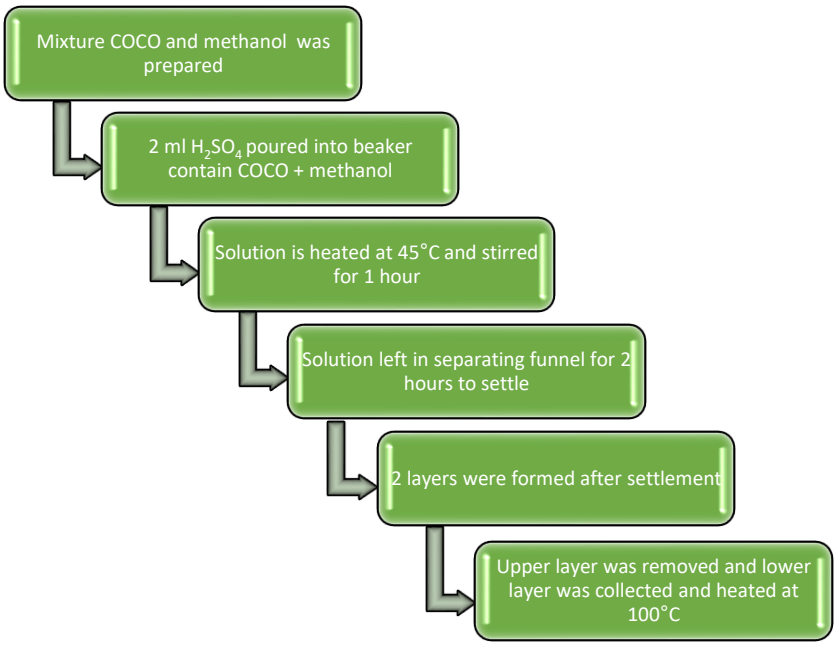

Figure 3.4 : Esterification Process Steps (Bello et al., 2015)

Crude coconut oil and methanol were mixed with ratio 0.2:1 molar ratio. Then, 2 ml sulphuric acid (H_2SO_4) (1 vol.% of 200 ml of oil taken) was added to the solution. The solution was then heated (45 °C) ± 2 and stirred continuously with magnetic stirrer for 1 hour. The solution was then left in the separating funnel for 2 hours. Two layers were visible after 2 hours settlement. The upper layer was an excess methanol and water while the lower layer was the esterified oil. The upper layer was removed, and the esterified oil was heated to 100°C to remove the remained impurities. The experiment was repeated with different parameters stated in Table 3.3. The repetition of the experiment helps in optimizing the esterification process. By exploring a range of catalyst to oil ratios, methanol to oil ratios, reaction times, and temperatures, researchers can identify the most favourable conditions for achieving a high esterification efficiency and product yield. This optimization is crucial for enhancing the overall performance and economic viability of the process (Bello et al., 2015).

3.6.2 Base Transesterification

Crude coconut oil transesterification process was performed using experimental matrix parameters listed in Table 3.4 and transesterification reaction condition matrix in Table 3.5 below :

Table 3.4 : Transesterification Experimental Matrix Process Parameters (Mohiddin, 2018)

Fixed Variables	Variable tested: Catalyst to Oil Ratio (w%/w%)						Observation
	CTO1	CTO2	CTO3	CTO4	CTO5	CTO6	
MTO, RT1, RT2	CTO1, MTO, RT1, RT2	CTO2, MTO, RT1, RT2	CTO3, MTO, RT1, RT2	CTO4, MTO, RT1, RT2	CTO5, MTO, RT1, RT2	CTO6, MTO, RT1, RT2	Optimum CTO, **CTO***
Fixed Variables	Variable tested: Methanol to Oil Ratio (v/v)						Observation
	MTO1	MTO2	MTO3	MTO4	MTO5		
CTO*, RT1, RT2	MTO1, CTO*, RT1, RT2	MTO2, CTO*, RT1, RT2	MTO31, CTO*, RT1, RT2	MTO4, CTO*, RT1, RT2	MTO5, CTO*, RT1, RT2		Optimum MTO, **MTO***
Fixed Variables	Variable tested: Reaction Time (hours)						Observation
	RT11	RT12	RT13	RT14			
CTO*, MTO*, RT2	RT11, CTO*, MTO*, RT2	RT12, CTO*, MTO*, RT2	RT13, CTO*, MTO*, RT2	RT14, CTO*, MTO*, RT2			Optimum RT1, **RT1***
Fixed Variables	Variable tested: Reaction Temperature (°C)						Observation
	RT21	RT22	RT23	RT24	RT25		
CTO*, MTO*, RT1*	RT21, CTO*, MTO*, RT1*	RT22, CTO*, MTO*, RT1*	RT23, CTO*, MTO*, RT1*	RT24, CTO*, MTO*, RT1*	RT25, CTO*, MTO*, RT1*		Optimum RT2, **RT2***

Table 3.5 : Transesterification Reaction Condition Matrix (Khan et al., 2021)

		CTO (w%/w%)							
		1	2	3	4	5			
		0.05	0.10	0.15	0.20	0.25			
MTO (v/v)									
1	2	3	4	5	6	7	8	9	10
1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	1:10
			RT1						
			1	2	3	4			
			1hr	2hrs	3hrs	4hrs			
		RT2							
		50°C	55°C	60°C	65°C	70°C			

Process flow of transesterification are shown in Figure 3.5 below :

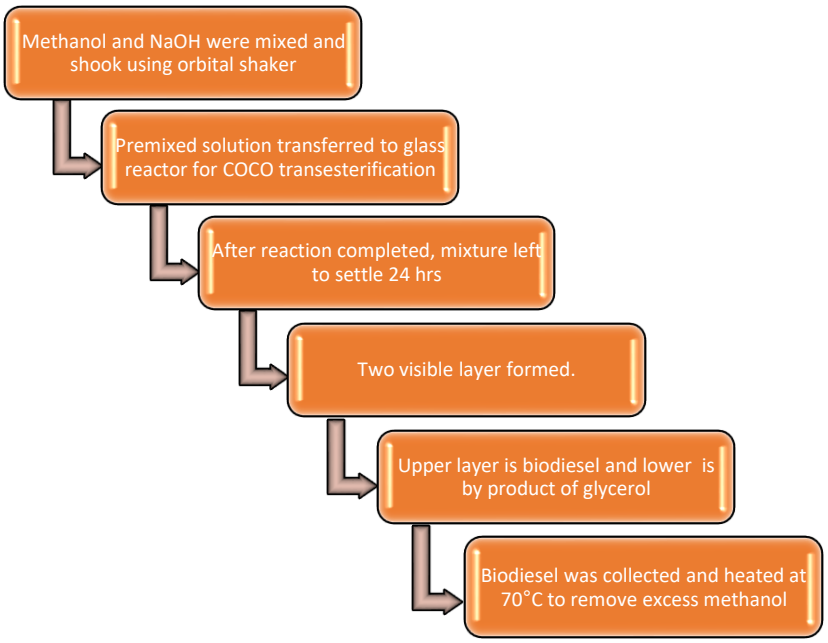

Figure 3.5 : Transesterification Process Steps (Reddy et al., 2017b)

A homogeneous catalyst which is sodium hydroxide (NaOH) used as a catalyst in the transesterification study of crude coconut oil. The parameters considered for transesterification included the molar ratio of oil to methanol, reaction temperature, reaction time and catalyst to oil ratio. The optimum parameters were determined for the highest yield of biodiesel. Transesterification of crude coconut oil was carried out using magnetic stirrer cum heater, thermometer and orbital shaker. Magnetic stirrer was used to stir the solution throughout the reaction (Buasri et al., 2013).

The molar ratio of oil to methanol used was 1:1 to 1:10. The reaction temperature used was between 50°C to 70°C. Reaction time used was 1 hour to 4 hours. Catalyst concentration used was 0.5% to 2.5% w/w (relative to oil weight). When a parameter was set, the other parameters were kept control. The control parameter was 1:6 oil to methanol molar ratio, 60°C reaction temperature, 2 hours reaction time and 1% catalyst concentration (Khan et al., 2021).

Prior to transesterification, methanol and sodium hydroxide were mixed and shook using orbital shaker at 250 rpm for 1 hour. The premixed solution was then transferred to glass reactor for transesterification with coconut oil. Once the reaction completed, the mixture was left to settle down for 24 hours. Two visible layers were formed where the upper layer was biodiesel while the lower layer was the used catalyst and by-product of glycerol. The lower layer of used catalyst and glycerol were then discharged, and the biodiesel were heated to 70°C to remove excess methanol (Reddy et al., 2017b).

The experiment was repeated with different parameters stated in Table 3.4 with reaction condition stated in Table 3.5. The experiment was repeated 3 times and the average biodiesel yield was calculated. The biodiesel yield was calculated by using the formula:

$$\text{Biodiesel Yield (\%)} = \frac{\text{(Experimental Yield)}}{\text{(Theoretical Yield)}} \text{ x } 100\%$$ (Shajaratun Nur et al., 2014) Equation 3.2

The optimum parameters for transesterification reaction which gives the highest yield of biodiesel was determined.

3.7 Physicochemical Properties Determination

The physicochemical properties of CB were determined by methods provided by European EN 14214 standard and American ASTM D6751 standard. The density at 15 °C was determined with a density meter (Anton Paar DMA 35). The flash point of CB was determined using a flash point tester (Seta Multiflash Automatic Flash Point - Universal Base Unit 34000-0). The acid value was determined by titration with KOH. The heating value of CB was determined through a bomb calorimeter (Fisher Parr 6400 Calorimeter). After the completion of biodiesel production, there was the need to determine the potential and properties of the coconut biodiesel. The coconut biodiesel was to go through a number of tests; such as density test, calorific value test and flash point test.

3.8 Biodiesel Blending

Biodiesel was blended with commercial diesel for analysis of the physical and chemical properties of the biodiesel blends. The biodiesel blends were also used in diesel engine for performance study. The blending percentage was shown in Table 3.6. The mixtures were then shook using orbital shaker for 1 hour for proper mixing.

Table 3.6 : Coconut Biodiesel Blend Formulation (Reddy et al., 2017b)

Biodiesel Blend	
B0	100% Diesel
B10	10% v/v biodiesel in conventional diesel
B20	20% v/v biodiesel in conventional diesel
B30	30% v/v biodiesel in conventional diesel
B40	40% v/v biodiesel in conventional diesel
B50	50% v/v biodiesel in conventional diesel

3.9 Engine Performance Test

All CB-petrodiesel blends were tested on a test diesel engine (Isuzu 4FB1). The calculation formula shown in Table 3.7. To begin with, the test engine was warmed up using petrodiesel before any testing session. The engine speed was varied from 800 rpm to 1800/3600 rpm and the throttle was set to 75% capacity during all engine test sessions (Khan et al., 2021). The sample CB-petrodiesel blend was filled through the engine's input valve and the engine was left running until 20 mL of the CB-petrodiesel blend consumed. The brake horsepower, engine power output, and specific fuel consumption were noted only when the readings were stable. CO and HC emissions were measured from the exhaust gas using a gas analyzer (Bosch ETT 008.36). Meanwhile, NOx emission was measured using another gas analyzer (Bacharach CA300NSX).

Table 3.7 : Calculation Formula Summary for Diesel Engine Performance (Reddy et al., 2015)

Parameters	**Definition**	**Formula**
Torque (T)	= brake load x radius	= N x r
Fuel Consumption Rate (FCR)	= fuel volume / time	= V / t
Engine Output Power	= (current x voltage x cos π) /1000W	$= \frac{IV\cos\pi}{1000}$
Specific Fuel Consumption (SFC)	= Fuel volume / power output	$= {}^{v}/_{P}$
Brake Horsepower (Bhp)	= 2π x speed x torque	= 2π x υ xT
Indicated Horsepower (Ihp)	= no. of cylinders on engine x mean indicated pressure in cylinders x cross sectional area of cylinder x number of working strokes per milimetre	$= \frac{NplAn}{1000}$
Mechanical Efficiency (η)	$= \frac{Bbp}{Ihp}$ x 100%	= %

CHAPTER 4

RESULT AND DISCUSSION

4.1 Crude Coconut Oil Acid Value Determination

The acid number indicates the number of carboxylic acid groups in a chemical substance. The acid number determines the level of biodiesel breakdown when the fuel is utilized (Swaroop et al., 2016). The amount of free fatty acids present in the oil was measured by titrating some samples of COCO against a standard base solution (Tiwari et al., 2013). The titration process was performed with the amount of KOH in mg required to neutralize 1g of fatty acid methyl ester to gain the acid value or the neutralization number.

$$Acid\ Value\ (mg\ KOH/g) = (MW_{KOH} \times N \times V)/W_s \qquad \text{Equation 4.1}$$

$$FFA\ content\ (\%) = (28.2 \times V \times N)/W_s \qquad \text{Equation 4.2}$$

Table 4.1: Results of Titration

Experiment	Weight, W (g)	Volume,V (ml)	Molarity, N (mol/L)	Acid Value (mg KOH/g)
1	2.772	14.7	0.1	29.755
2	2.873	15.0	0.1	29.295
3	2.763	14.5	0.1	29.446

Table 4.2: COCO Acid Value and FFA Content

Titration	**Acid value (mg KOH/g)**	**FFA content (%)**
1	29.755	14.95
2	29.295	14.72

Table 4.2 continued

3	29.446	14.79
Average	**29.499**	**14.82**

From the titration, the average acid value obtained was 29.499 mg KOH/g which indicates FFA content of 14.8%. Several variables influence high FFA content in edible and non-edible oil, including the type and quality of the raw materials used, the conditions during collection, processing, and storage, as well as the oil's age and degree of deterioration, influenced (Di Pietro et al., 2020). According to Silitonga et al. (2013), the vegetable oil contains a high amount of free fatty acids (>1%). It cannot be converted directly into biodiesel using an alkaline-catalyzed transesterification process due to increased chances of forming soap when free fatty acids and an alkali catalyst react. Crude coconut oil must undergo a pre-treatment to reduce FFA value before based catalyzed transesterification. Hence, two-step transesterification was chosen (Silitonga et al., 2013).

4.2 Biodiesel Production

4.2.1 One Step Transesterification

The average acid value obtained from the titration was 29.5% which is very high and makes one-step transesterification by using a base catalyst not applicable. As the acid value is too high, one-step transesterification is unsuitable for CB production. High FFA in the oil deactivates the trigger, and the addition of excess catalyst as compensation gave rise to emulsion formation, which increased the viscosity, leading to the formation of gels and the problems associated with glycerol separation and loss in ester yields (Silitonga et al., 2013).

4.2.3 Two Step Transesterification

First, the experiment started with an acid pre-treatment or esterification process to reduce the free fatty acid (FFA) by converting it into esters. Theoretically, esterification will also help increase biodiesel yield (Yusoff et al., 2013). After esterification, base catalyzed transesterification is carried out to produce CB.

Biodiesel production yield depends on a few factors, which are catalyst to oil ratio, methanol to oil ratio, reaction time, and reaction temperature for producing biodiesel (Silitong et al., 2013; Tiwari et al., 2013). Transesterification is performed according to the factors mentioned to obtain the optimal condition to produce high quality CB.

4.2.3.1 Effects of Catalyst Concentration on Coconut Biodiesel Yield

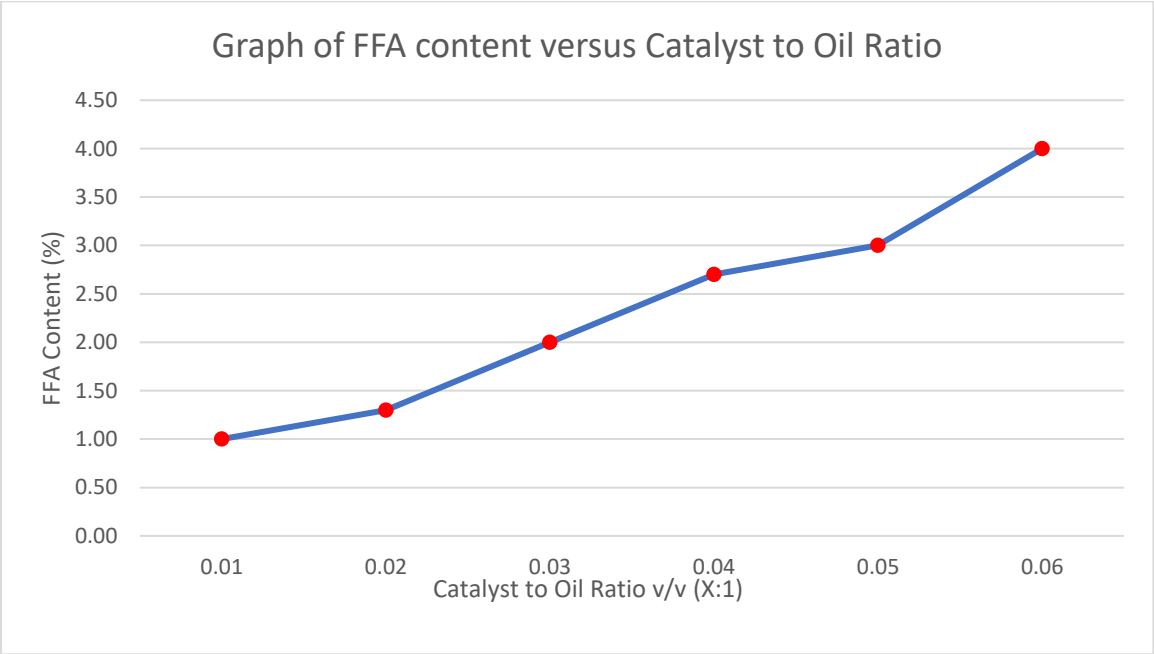

Figure 4.1 : Graph of FFA Content versus Catalyst to Oil Ratio for Acid-Catalyzed Esterification

The results of the acid catalyzed esterification process are shown above in Figure 4.1. After the pre-treatment process, the FFA content of the crude coconut oil sample was

successively reduced to 1 %. The most effective ratio was 0.01 v/v catalyst to oil ratio, as the FFA content dropped to 1% after the acid-catalyzed esterification. As the catalyst to oil ratio increased, the FFA content increased, resulting in decreased ester yield (Tiwari et al., 2013). Hence, the optimum catalyst to oil ratio by volume of sulphuric acid is 0.01 v/v, which reduces the FFA content to 1% (Goyal et al., 2013).

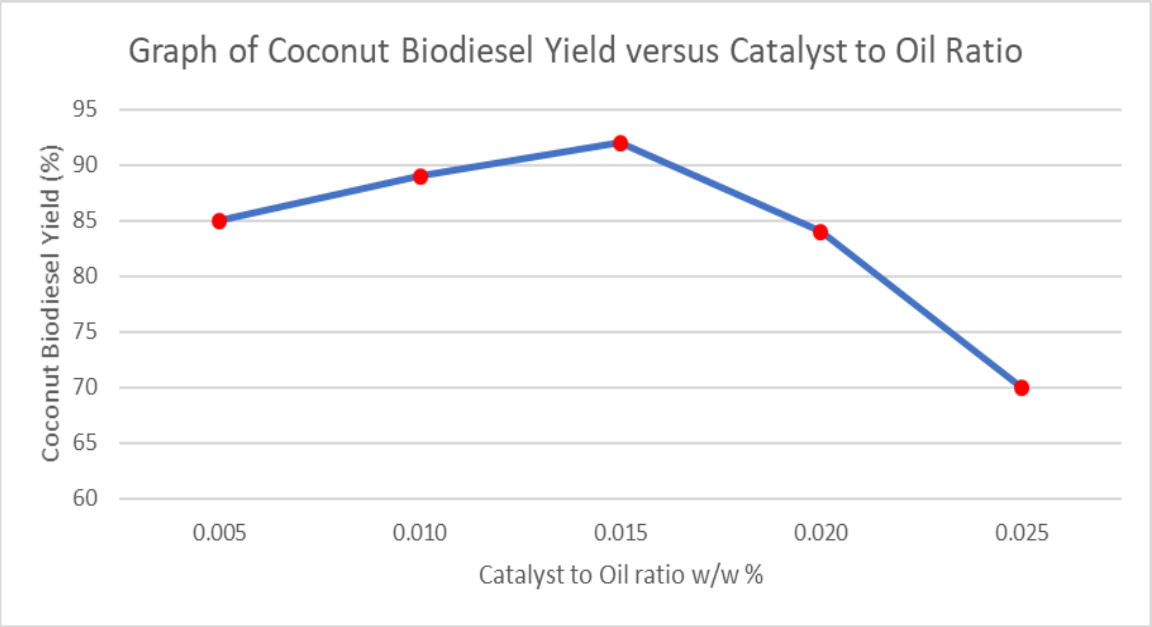

Figure 4.2 : Graph of Coconut Biodiesel Yield versus Catalyst to Oil Ratio for Base Catalysed Transesterification

Catalyst to oil ratio plays a very significant role in the transesterification process, and based catalyst is said to be 4,000 times faster than an acid catalyst (Pathak, 2015). The NaOH was used as a catalyst for conversion of biodiesel. It was found that catalyst to oil ratio was increased from 0.5% w/w to 1.5% w/w steadily; however, by further increase of catalyst ratio, biodiesel yield decreased.

The optimum catalyst to oil ratio was 0.015:1 (NaOH : Oil), with the highest coconut biodiesel yield of 92%. Hence, the increase in catalyst concentration did increase the biodiesel yield conversion (Reddy et al., 2015). However, further increasing catalyst

concentration surpassing the optimum condition will only result in lower biodiesel yield as the rate of soap formation increases (Reddy et al., 2015). Higher catalyst concentration not only can give higher biodiesel yield but also increases the risk of saponification reaction to occur (Boonmee et al., 2010). Furthermore, this excess amount of catalyst increased the reactants' viscosity, resulting in lower biodiesel yield, as reported by (Nakpong & Wootthikanokkhan, 2010).

4.2.3.2 Effects of Methanol to Oil Ratio on Coconut Biodiesel Yield

Optimizing the methanol to oil ratio is crucial (Raheem et al., 2020). Sulphuric acid H_2SO_4 and sodium hydroxide NaOH are chosen as the catalyst for esterification and transesterification process with different methanol to oil ratios.

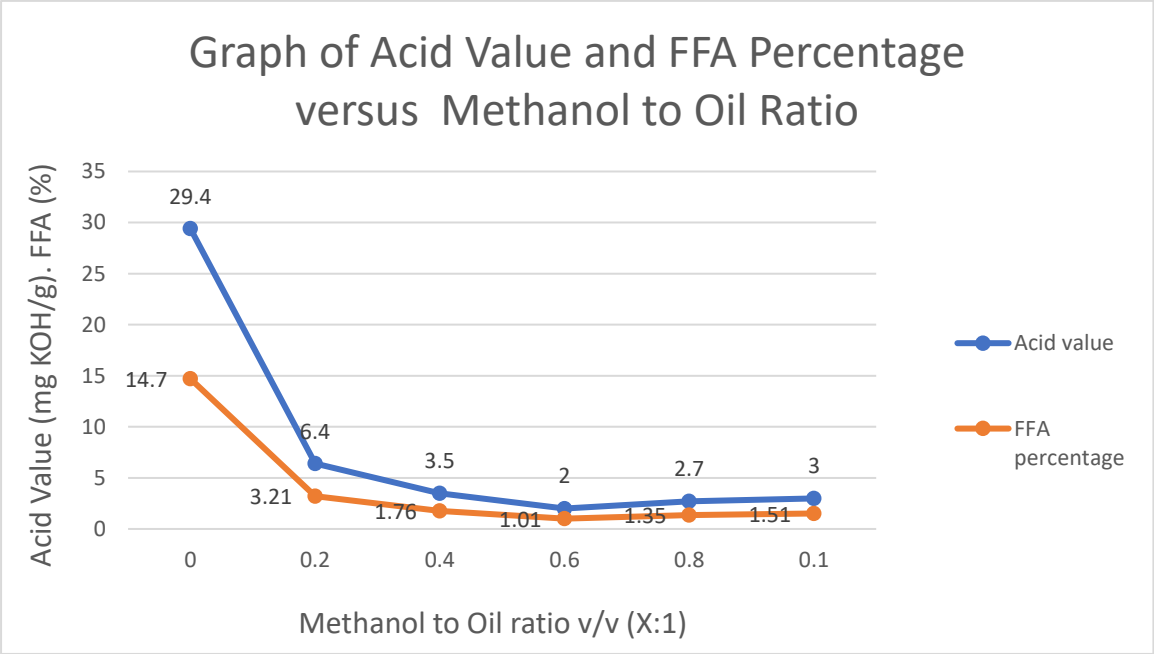

Figure 4.3 : Graph of Acid Value and FFA Percentage versus Methanol to Oil Ratio for Acid Catalysed Esterification

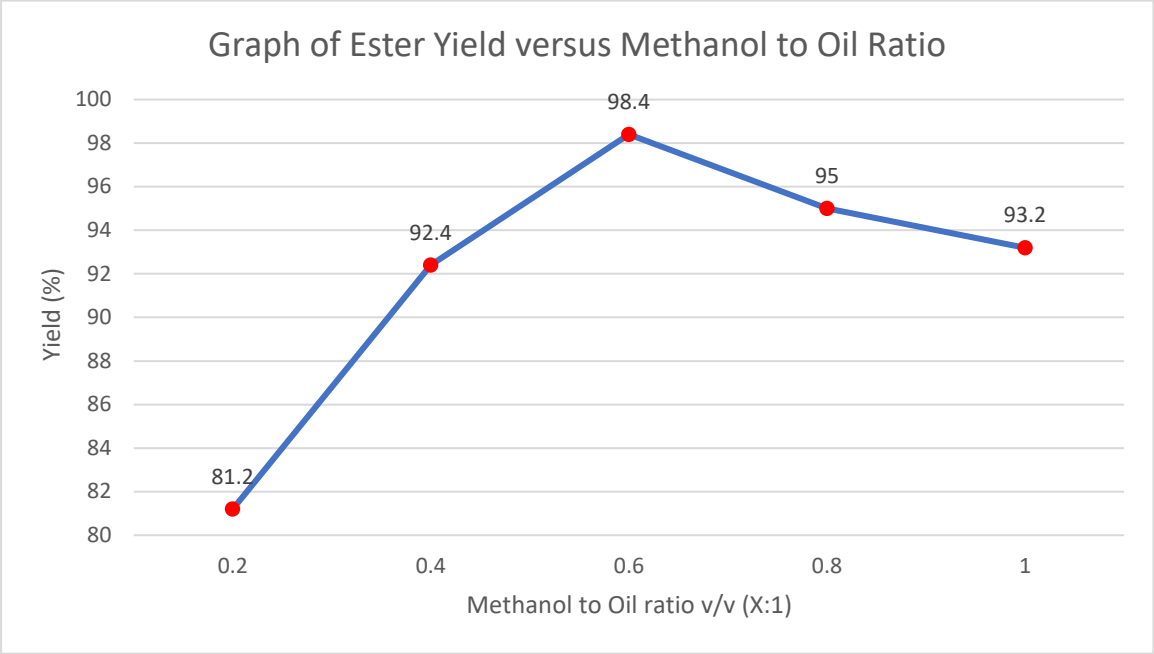

Figure 4.4 : Graph of Ester Yield versus Methanol to Oil Ratio for Acid Catalysed Transesterification

Figure 4.3 above shows the effect of different methanol to oil ratios on the acid value and FFA percentage. The molar ratio of methanol to oil at 0.6:1 v/v shows the lowest FFA percentage of 1.01 % and acid value of 2 mg KOH/g. The result indicates that the molar ratio of methanol to oil 0.6:1 v/v is the optimum condition for the esterification process.

Ester yield is calculated as the percentage of esters produced in the reaction compared to the total amount of oil used in the esterification process. It is a measure of the efficiency of the esterification reaction in converting the triglycerides in the oil into esters (biodiesel) (Al-Zuhair et al., 2015). The formula for calculating ester yield is as follow:

Ester Yield (%) = (Mass of esters produced / Mass of oil used) x 100 Equation 4.1

To calculate the mass of esters produced, the acid value of the biodiesel and the mass of the oil used are required. The acid value represents the amount of free fatty acids (FFA) present in the biodiesel, which indicates the level of unreacted triglycerides in the final

product. The acid value is typically expressed in milligrams of potassium hydroxide (KOH) required to neutralize one gram of the biodiesel sample.

The optimum methanol to oil ratio for acid-catalyzed esterification process is 0.6:1 (v/v) which gives the ester yield of 98.4%. Ester yield did not increase with methanol to oil ratio v/v 0.8 and 1.0. Both ratios lost 3.4% and 5.2% of ester yield, respectively. Further, increasing the amount of methanol more than the optimum condition does not significantly affect the FFA percentage or the acid value. Excess methanol will have greater effects than catalyst concentration, thus decreasing the ester yield. Greater methanol to oil ratio in the esterification process will only reduce the efficiency of H_2SO_4 (Bouaid et al., 2012). In addition, increased methanol to oil ratio greater than optimal condition is insignificant in the reduction of acid value. It is not economical as biodiesel production costs are essential (Nakpong & Wootthikanokkhan, 2010). The highest ester yield was observed at the optimum methanol to oil ratio of 0.6:1 (v/v), indicating that this ratio resulted in the most efficient conversion of triglycerides to esters during the acid-catalyzed esterification process.

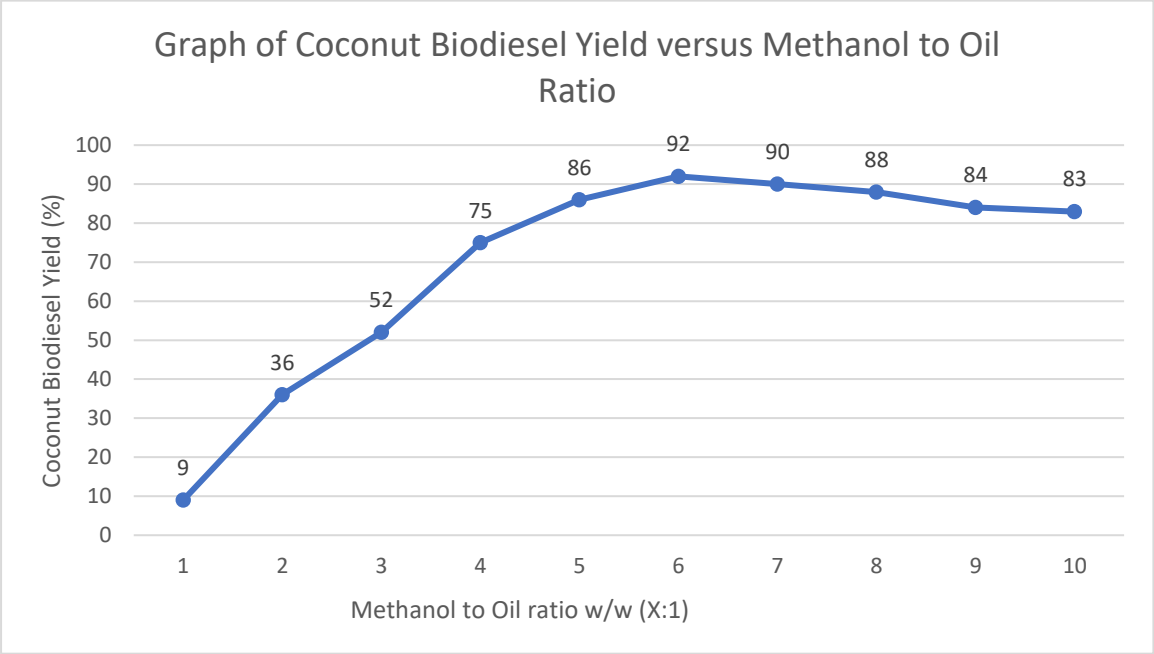

Figure 4.5 : Graph of Coconut Biodiesel Yield versus Methanol to Oil Ratio for Base Catalyzed Transesterification

Figure 4.5 shows the biodiesel conversion rate using catalyst (NaOH). The best conversion rate of coconut methoxide to biodiesel is 6:1 w/w methanol to oil ratio, with the highest yield of 92%. The excess of methanol is necessary because it can increase the rate of methanolysis. The use of excess methanol in the transesterification reaction was essential to ensure complete feedstock conversion (Nakpong & Wootthikanokkhan, 2010). On the other hand, any further increase in crude coconut oil to methanol molar ratio has decreased the CB yield. The higher molar ratio of methanol to oil showed 7-10 w/w methanol to oil ratio decrease in CB yield. Excess alcohol used in transesterification will not benefit because it will only increase the glycerol's solubility rate, leading to the decreasing CB yield rate (Reddy et al., 2015, 2017b). Increasing the molar ratio beyond the optimum amount will only lead to an unnecessary increase in production cost. Biodiesel washing to remove the excess catalyst, and methanol usually present with the final product (biodiesel) are the additional cost to be controlled (Akhihiero et al., 2013).

4.2.3.3 Effect of Reaction Time on Coconut Biodiesel Yield

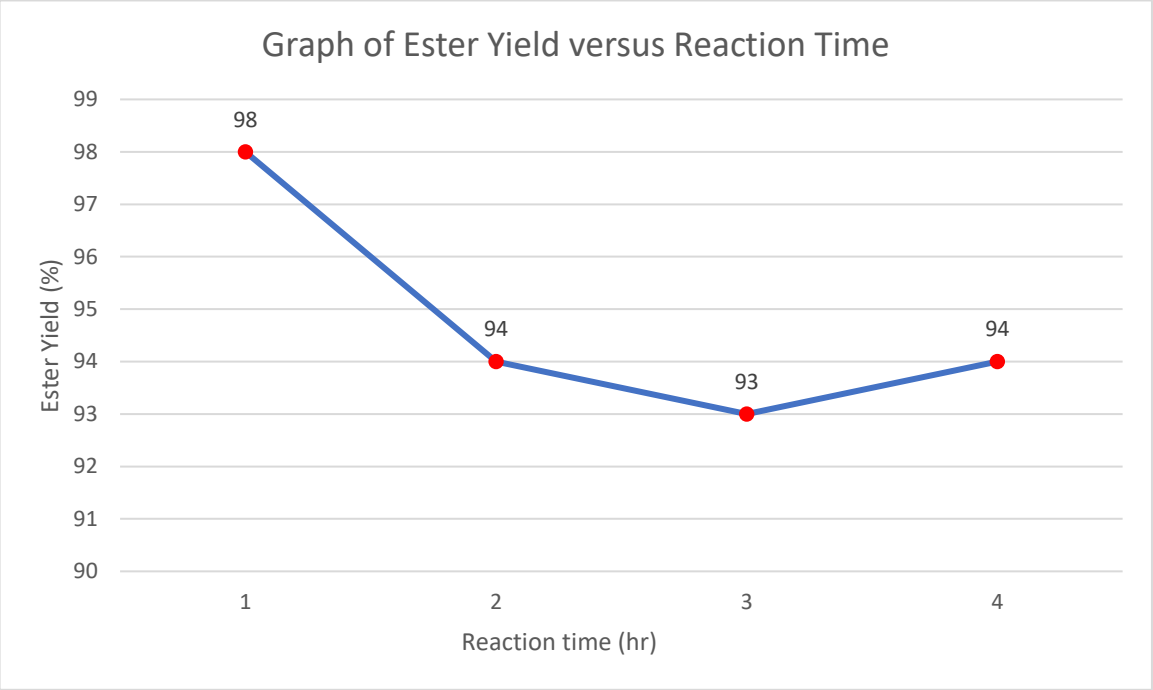

Figure 4.6 : Graph of Ester Yield versus Reaction Time

Based on Figure 4.6, among the 4-reaction time experimented, one-hour reaction time shows the highest ester yield with 98%. The reaction time of more than an hour yield dropped below 95%, as shown in the graph above. Hence, the optimum reaction time for the esterification process is one hour. Increasing the reaction time did not significantly affect the rate of ester yield. Further increasing the reaction time will convert the ester yield back to crude oil because the esterification is reversible (Nakpong & Wootthikanokkhan, 2010; Reddy et al., 2015). Additional reaction time decreases ester yield due to the effect of water formation during the esterification of FFAs, which prevents further reaction (Nakpong & Wootthikanokkhan, 2010).

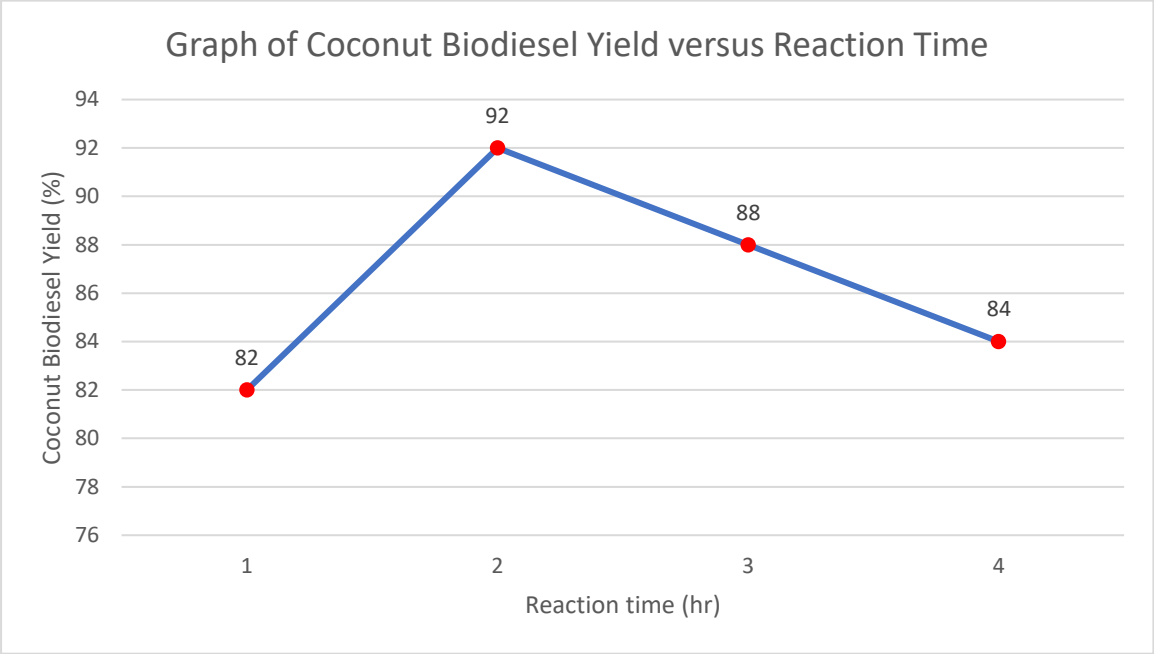

Figure 4.7 : Graph of Coconut Biodiesel Yield versus Reaction Time

For the transesterification process, among the 4-reaction time experimented, 2 hours reaction time resulted in the highest biodiesel yield of 92%. Other reaction time experiments, which are 1,3, and 4 hours, only produce 82%, 88%, and 84 % of biodiesel yield. The optimum time for the base-catalyzed transesterification process is two hours. This means the maximum rate of biodiesel conversion is only two hours. For the transesterification process to complete its reaction, ample time must be given.

Nevertheless, extended reaction time has a negative effect on biodiesel yield (Nakpong & Wootthikanokkhan, 2010). This is consistent with the fact that transesterification is a reversible reaction (Baskar et al., 2018; Reddy et al., 2017a). Exceeding the optimum condition of biodiesel conversion rate time leads to a bigger risk of reversible reaction and emulsion formation, decreasing biodiesel yield.

4.2.3.4 Effect of Reaction Temperature on Coconut Biodiesel Yield

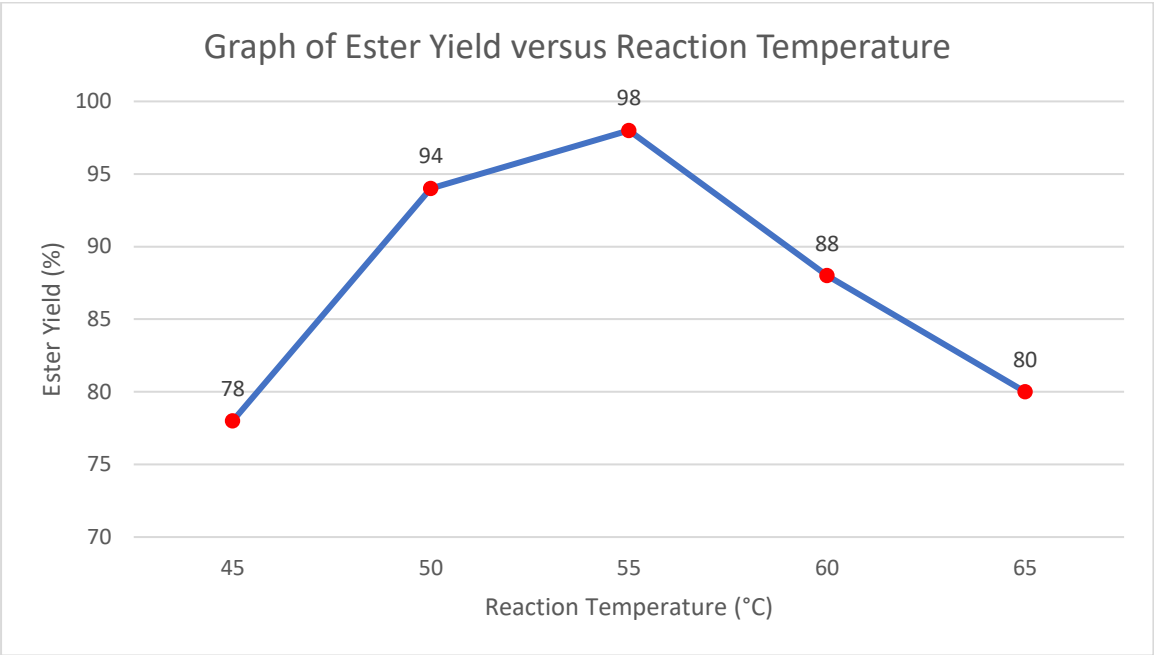

Figure 4.8 : Graph of Ester Yield versus Reaction Temperature

From Figure 4.8, the ester yield increased with the increase in reaction temperature. However, an increased ester yield only occurs between 45 °C and 55 °C. Reaction temperature beyond 55 °C decreases in ester yield from 60 °C to 65 °C. The best reaction temperature for acid-catalyzed transesterification is 55 °C, obtaining an ester yield of 98%. A lower reaction temperature did not give a high ester yield because the reaction was not vigorous enough as the energy supply was low. The solvent reaction is not maximized within an hour. More time is needed for greater yield (Boonmee et al., 2010). As for higher reaction temperature, a lower yield rate occurs because of the loss of methanol due to evaporation. Hence, the methanol amount to complete the reaction is insufficient.

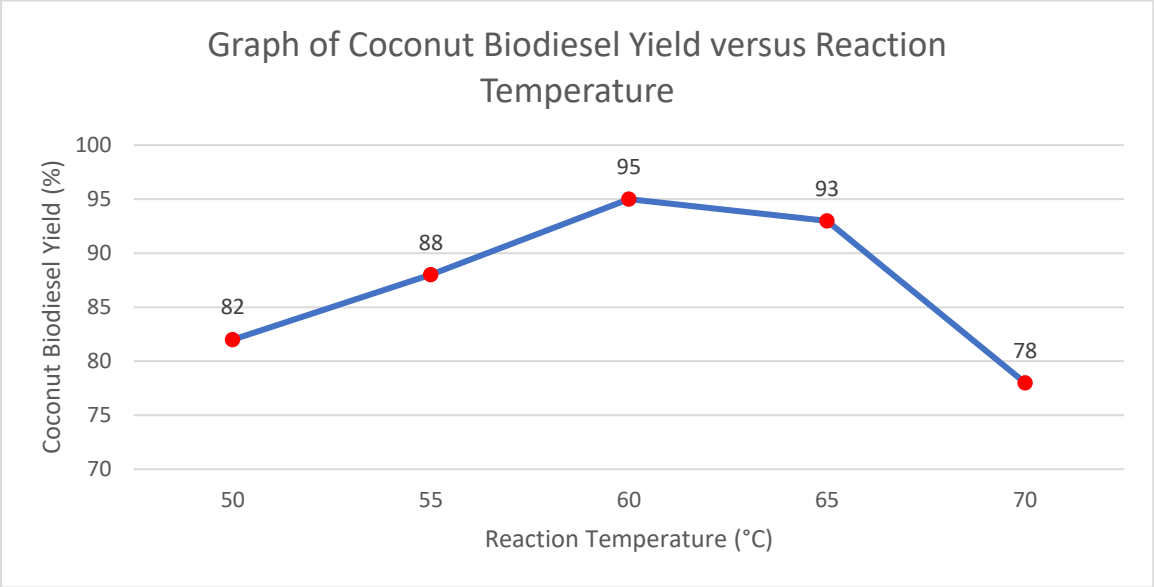

Figure 4.9 : Graph of Coconut Biodiesel Yield versus Reaction Temperature

The experimental result of coconut biodiesel yield obtained is shown in Figure 4.9 above. The graph shows increased reaction temperature increased biodiesel yield but only up to a specific temperature. From 50 °C to 60 °C, the yield was going uptrend. However, beyond 60 °C, biodiesel yield drops. Therefore, the best yield rate was at 60 °C with 95% biodiesel yield. High reaction temperature will increase the rate of biodiesel conversion rate (Bambase et al., 2021; Silitonga et al., 2013). The oil's viscosity decreases as the reaction temperature rises and increases the solubility of the oil in the methanol (Boonmee et al., 2010). In contrast, a higher reaction temperature gives excessive energy and triggers the saponification process, resulting in lower biodiesel yield (Koh & Tinia, 2011).

However, higher temperatures of more than 70 °C are not recommended due to the boiling point of methanol. As the temperature increases and reaches the boiling point of methanol, the methanol will quickly vaporize and form many bubbles, inhibiting the reaction on the two-phase interface, thus decreasing the biodiesel yield (Esmaeili & Foroutan, 2018).

4.3 Characterization of Coconut biodiesel

4.3.1 Physicochemical Properties of Coconut Crude Oil and Coconut biodiesel

From the results, COCO cannot be used directly as a biodiesel as its density and acid value exceed the standard limit. Thus, converting COCO into biodiesel (in this case, CB) was recommended for it to be utilized as a fuel. CB possessed the physicochemical value required by EN 14214 for it to be used as an automotive diesel fuel. CB's density at 873 kg/m^3 was well within the limit. Engine problems associated with fuel injection and thermal efficiency may arise if the diesel fuel's density is not standard (Sakthivel et al., 2018).

The CB's flash point is higher than the lower limit established by EN 14214. The COCO's flash point was even higher than petrodiesel, which is generally true for most biodiesel (Mat Yasin et al., 2017). Fuel with a high flash point is safer to handle, transport, and store (Boey et al., 2011).

The acid value of biodiesel and other fuel properties correlates to its oxidation and storage stability (Mahmudul et al., 2017). Lower acid value has been attributed to longer storage stability (Saluja et al., 2016). CB's acid value was well below the maximum limit of 0.5 mg KOH/g set up by EN 14214.

When burned, the energy in 1 kilogram of fuel is characterized by its HHV which is a crucial characteristic. Since biodiesel contains approximately 10% more oxygen than diesel (Bello et al., 2015) and coconut oil has 85% molecules with chains of 12 and 14 carbons, the HHV value of coconut biodiesel is 38.329 MJ/kg, which is lower than diesel's value of 46.365 MJ/kg. This factor influences how many calories are contained in biodiesel made from coconut oil. The heating value was increased by COCO conversion to CB. CB's heating value was 38.329 MJ/kg, which was 17.33% lower than the heating value of petrodiesel

(46.365 MJ/kg) (Ali et al., 2015). The lower heating value was predicted as one of the biodiesel's general drawbacks (Mat Yasin et al., 2017).

Table 4.3 : Physicochemical Properties of Coconut Crude Oil and Coconut Biodiesel

Properties	COCO	CB	Standard	Limit
Density at 15°C (kg/m^3)	926	873	EN 14214	860 – 900
Viscosity (cSt)	27.65	2.71	ASTM D6751	1.9-6.0
Flashpoint (°C)	Not Tested	110	ASTM D93	≥100
Acid value (mg KOH/g)	2.12	0.15	D6751	<0.5
Heating value (MJ/kg)	37.634	38.329	EN14213	≥35.000

4.4 Diesel Engine Mechanical Performance Optimization

The performance of CB blends is tabulated as shown in Table 4.4 below for further analysis by the graph plotted below.

Table 4.4 : Experimental Results of Diesel Engine Testing for B0 to B50 Blends

CB Blends	B0	B10	B20	B30	B40	B50
Torque (N.m)	30	30	30	30	30	30
Fuel Consumption rate (mL/s)	0.325	0.332	0.326	0.336	0.341	0.345
Engine Power Output (kW)	2.472	2.440	2.453	2.409	2.399	2.368
Specific Fuel Consumption (mL/kW)	8.090	8.196	8.152	8.303	8.335	8.446
Brake Horsepower (kW)	35.412	35.333	35.373	35.274	35.244	35.184

Table 4.4 continued

Indicated horsepower (kW)	57.800	57.800	57.800	57.800	57.800	57.800
Mechanical efficiency, η (%)	61.267	61.130	61.192	61.028	60.975	60.873

The power generated by the engine under loading was lower for CB blends compared to petrodiesel (B0). The engine power output decreased with the increment of the CB blending percentage. The power output for B0, B10, B20, B30, B40, and B50 were 1.2.472, 2.440, 2.453, 2.409, 2.399 and 2.368, respectively. The differences are insignificant. The CB-petrodiesel blends had lower power output because of the low heating value of CB. This result was in accordance with other studies that have been done (Mahmudul et al., 2017).

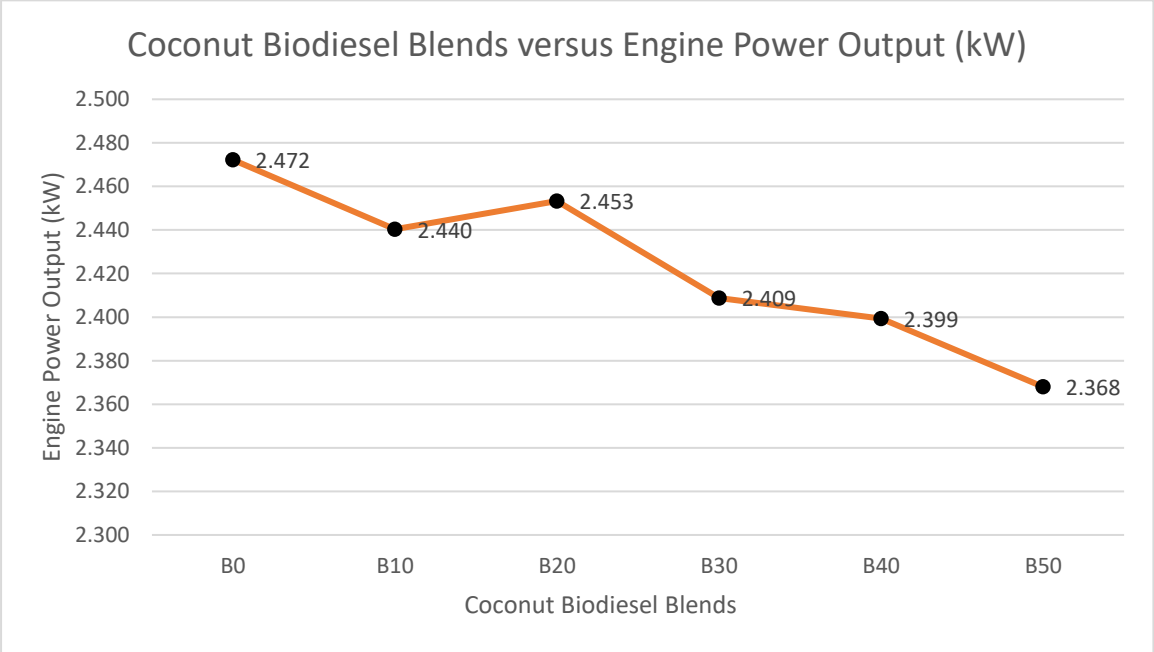

Figure 4.10 : Graph of Coconut Biodiesel Blends versus Engine Power Output

Specific fuel consumption is widely used as a measure of atmospheric engine performance. It is defined as the weight flow rate of fuel needed to produce a unit of power.

It describes the diesel engine's fuel efficiency with respect to the power output, which allows the efficiency of different fuels to be directly compared. The smallest value of specific fuel consumption indicates that a small amount of energy is required to regenerate a unit of power output by the diesel engine. The equation for the specific fuel consumption is as below:

Specific fuel consumption = (fuel flow)/(power output) Equation 4.3

The fuel volume was used in the project, instead of the mass of fuel, since biodiesel production was in volume. Even though volume usage depended on temperature, this factor was not counted since it did not affect the experiment. Moreover, the blends were stored at room temperature, and the experiment was conducted at room temperature. The figure below shows the specific fuel consumption versus all blends.

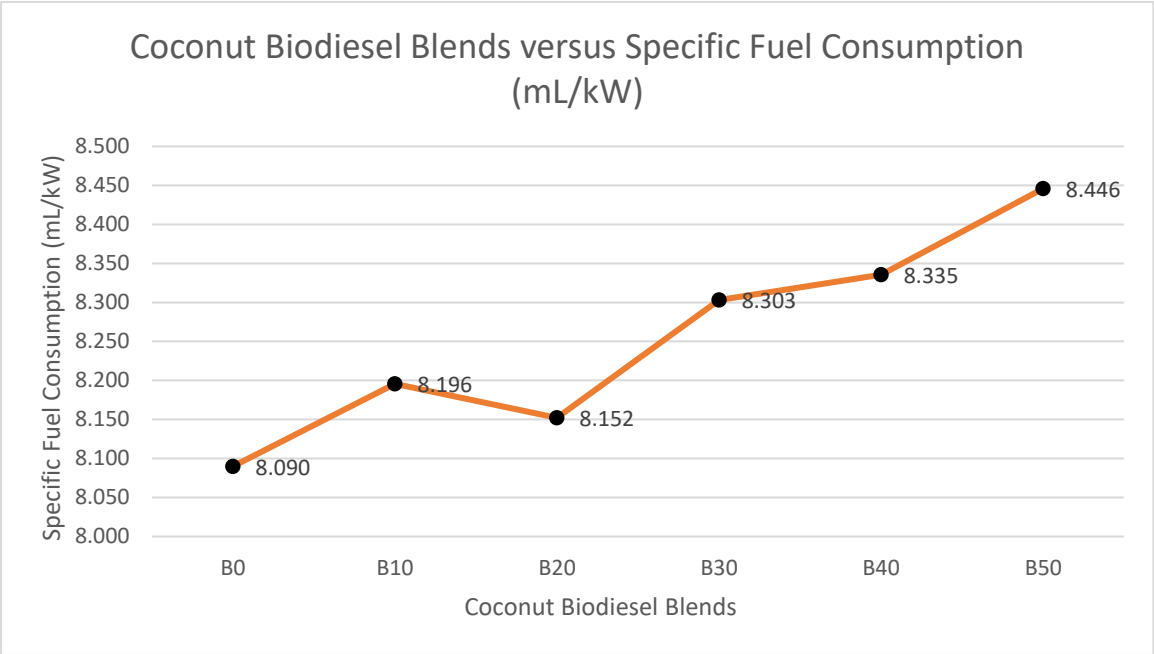

Figure 4.11 : Coconut Biodiesel Blends versus Specific Fuel Consumption

Figure 4.11 shows specific fuel consumptions of different CB blends. Mineral diesel has the lowest specific fuel consumption than CB blends because it has a higher energy content. CB blends' lowest specific fuel consumption is 8.152 mL/kW, which is B20. From

Figure 4.11, B50 consumed the highest value of specific fuel consumption, 8.446 ml/kW. B40 had the second highest value, 8.335 ml/kW, followed by B30, 8.303 ml/kW, and B10, 8.196 ml/kW. B50 was the less preferable since it required the largest amount of fuel to generate ml/kW of power output. Therefore, B20 was the most preferable compared to the other blends. This is due to the usage of B20 leading to energy savings and reducing the fuel cost while balancing its performance.

Thus, we can deduce that B20 is comparable to pure diesel as it shows almost similar value to B0. This shows the potential of B20 as a fuel alternative to mineral diesel. The increment resulted from CB having a lower heating value compared to petrodiesel. The differences on the specific fuel consumption between B0 to B10, B20, B30, B40, and B50 are 1.31%, 0.77%, 2.63%, 3.02%, and 4.40% respectively. The differences are insignificant. The difference in specific fuel consumption between petrodiesel and CB blends was predictable, as other studies have suggested (Emiroğlu et al., 2018; Hasan & Rahman, 2017; Sundus et al., 2017).

The brake power of an engine is the raw power generated by the engine at the engine's shaft, without any loss to auxiliary components or any attachment of the engine (Yang et al., 2012). By calculating the brake horsepower of a diesel engine, the output delivered can be determined to ensure that the output is adequate to drive the motor and auxiliary components. Besides, one can calculate the amount of work required to allow the motor to operate at peak efficiency. Figure 4.12 shows the brake horsepower of the diesel engine versus all blends.

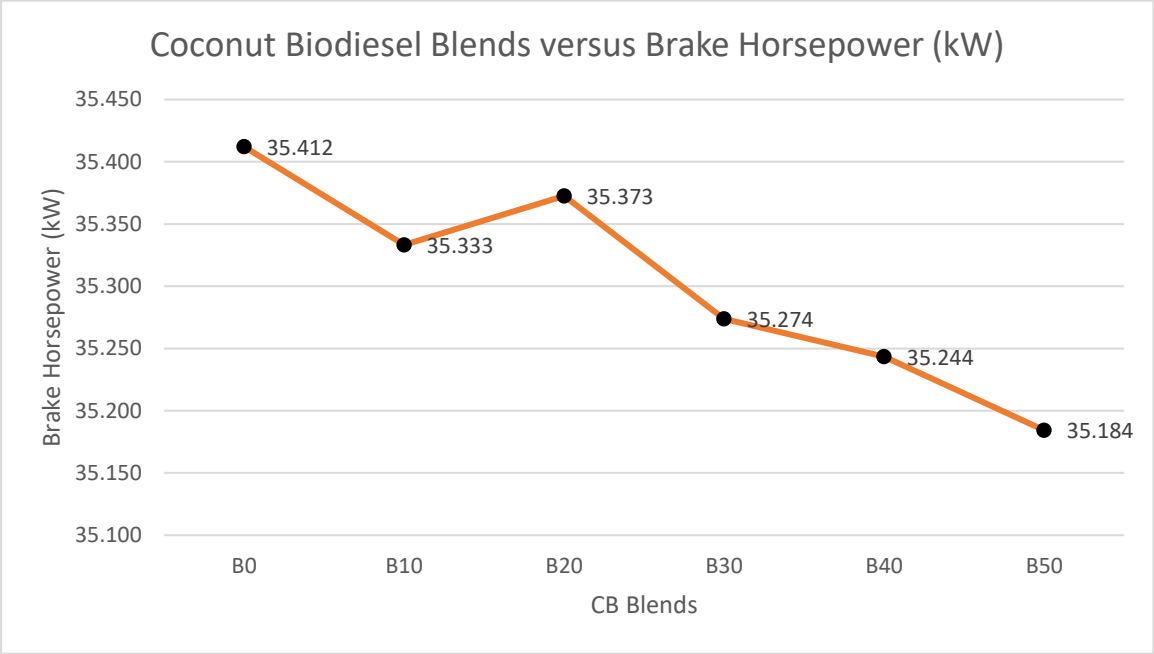

Figure 4.12 : Coconut Biodiesel Blends versus Brake Horsepower

B0, or pure diesel, has the highest brake horsepower while CB blends; B20 is the highest among them, with 35.373 kW. From Figure 4.12, the lowest brake horsepower was obtained using B50, which was 35.184 kW. The brake horsepower value increased when B40 was used, 35.244 kW, followed by B30, 35.274 kW. B10 had the second-highest brake horsepower, which was 35.333 kW. The decreasing result of B30 to B50 is due to the lower calorific value and high viscosity of the blends, which affect the engine's combustion. The most increased brake horsepower among CB blends indicates that B20 had the highest output, allowing both motor and auxiliary components to operate well. Other than that, the highest brake horsepower achieved by B20 showed that by using it, the diesel engine delivered the largest power at the highest peak of efficiency and the largest capacity. This variation was caused by CB blending and engine operating conditions, which were uncontrolled (Hernández-Cruz et al., 2016). Overall, the brake power increased along with the CB blending percentage.

Mechanical efficiency is usually used to measure the effectiveness of a machine and can be defined by the equation below:

Mechanical efficiency is the ratio of work input over output, expressed in percentage (%). The efficiency of the ideal diesel engine is 100%, but the actual efficiency will always be less than 100% because some work done by the system is lost and transformed into thermal energy.

In this experiment, the work output was the brake horsepower, and the work input was indicated horsepower, as shown in the equation below:

Indicated horsepower is the theoretical power of a reciprocating engine if it ultimately has no friction in transferring the expanding gas energy in the cylinders. A device called an engine indicator measures the pressure developed in the cylinders to calculate indicated horsepower.

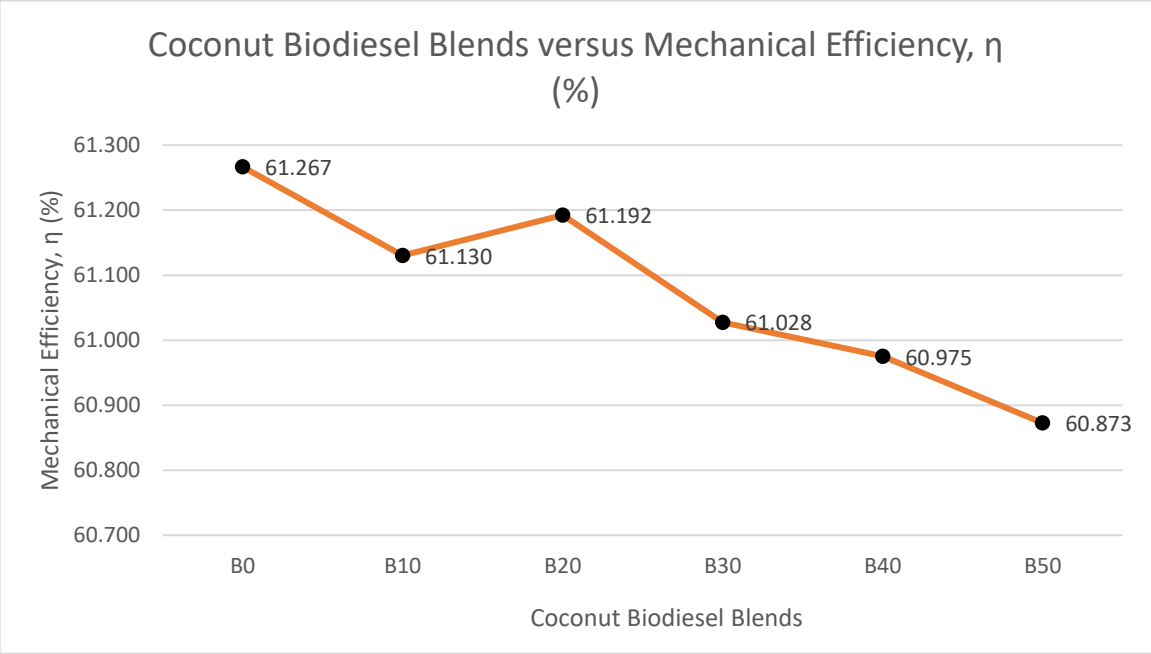

Figure 4.13 : Coconut Biodiesel Blends versus Mechanical Efficiency

According to Figure 4.13, the highest mechanical efficiency was achieved by B20, 61.192%, while the second highest is B10, 61.130%. It is followed by B30 61.028%, B40 60.975%, and B50 60.873%. The highest mechanical efficiency by B20 indicated that it was the best fuel for delivering the work output reciprocated to its work input. This also indicates that the value achieved by B20, 61.192%, was closest to petrodiesel, 61.267%. It shows that B20 has a better performance compared to pure diesel.

4.5 Diesel Engine Exhaust Gas Emission Ooptimization

Table 4.5 : Results of Emission Analysis of Petrodiesel dan Coconut Biodiesel

Component	Petrodiesel (ppm)	CB (ppm)
CO	1277	513
SO_2	3	1
NO	2	1
NO_2	0.4	0.2

Table 4.5 continue

NO_X	2	4
HC	25	13

CO, SO_2, NO, NO_2 and HC emissions were lower in CB, as shown by the result findings in Table 4.5. CB conducts a more thorough combustion process because of its higher cetane count. Additionally, biodiesel's high oxygen concentration improves combustion (Habibullah et al., 2015). Lower CO emission of CB is achieved using biodiesel fuel, which has a higher cetane number and oxygen content but less carbon and hydrogen content than diesel fuel (Tan et al., 2012). Biodiesel generally has high oxygen content, which induces complete combustion and less CO emission (Najafi, 2018; Omidvarborna, 2016; Rao et al., 2015). In contrast, the superior fuel characteristics of CB are responsible for the decrease in SO_2, NO, NO_2 and HC (Islam et al., 2014).

The NO_x emission level decreased as the CB blend percentage increased. This is since using biodiesel allows for enhanced combustion, which raises the temperature in the combustion chamber and the amount of oxygen present, both of which cause more NO_x to be produced. Complete combustion leads to less NO_x emission (Najafi, 2018). However, some literature recorded higher NO_x emissions with more increased biodiesel blending (Reddy et al., 2015). This was caused by higher heating value biodiesel having higher combustion temperature.

In addition, because biodiesel has a higher cetane number, its advanced combustion is facilitated by a shorter ignition latency. The higher bulk modulus of elasticity and higher cetane number of biodiesel blends than diesel can also cause their increased NO_x emissions (Habibullah et al., 2015).

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

After conducting series of experiments, all of the objectives stated in chapter one are achieved. Conclusions for all the objectives are stated in this chapter. These includes the biodiesel conversion method, optimum conditions of CB production, fuel properties and composition, optimum blend ratio and performance of diesel engine using CB blends. In this chapter, also included are some recommendations for practical improvements in future research. Lastly, further studies and potential research scope are included as additional idea from the writer.

5.2 Biodiesel Conversion

As discussed in previous chapters, transesterification method is the most preferable in production of biodiesel because of its cost effective and clean quality biodiesel yield. Also, transesterification is the best method is because of its renewability and sustainability (Koh & Tinia, 2011). In addition, transesterification was found to be the most effective way to reduce the viscosity of the highly viscous vegetable oil which can cause clogging in diesel engine (Meher et al., 2006; Singh & Padhi, 2006; Yogish et al., 2012). Biodiesel produced by transesterification can be used directly without engine modification needed (Parawira, 2010). The two-steps transesterification was performed because of the high FFA value of COCO. The acid catalysed esterification was carried out to reduce the FFA value followed by the base transesterification for biodiesel conversion. A high quality and clean CB was produced from transesterification method.

5.3 Optimum Conditions for Coconut Biodiesel Conversion

In the first step, acid esterification process, optimum catalyst to oil ratio obtained was 0.01:1 and the methanol to oil ratio was 60% (v/v). For base catalysed transesterification process, the best catalyst to oil ratio identified was 0.01:1 with the methanol to oil ratio of 6:1 (Boonmee et al., 2010). For reaction, in the acid pretreatment process, one hour of reaction time is the most suitable but for base transesterification needed two hours to have the optimum reaction time (Yusoff et al., 2013). Optimum reaction temperature for the step one is 55 °C whereas for second step is at 60 °C (Leung et al., 2010). This is due to better mixing intensity compared to magnetic stirrer.

Mixing intensity plays a crucial role in chemical reactions, especially in the context of biodiesel production through esterification and transesterification processes. Proper mixing ensures that reactants are thoroughly mixed and come into contact with the catalyst, promoting efficient and uniform reaction rates (Nagarajan et al., 2018).

In the case of esterification and transesterification processes for biodiesel production, mixing intensity directly affects the rate of reaction and the distribution of reactants. Efficient mixing can enhance the contact between the reactants (coconut oil, methanol, and catalyst) and the catalyst, leading to more effective conversion of triglycerides into fatty acid methyl esters (FAMEs), which are the main components of biodiesel.

Using a higher mixing intensity, such as a mechanical stirrer, as opposed to a magnetic stirrer, ensures better dispersion of reactants and catalyst throughout the reaction mixture. This reduces the chances of localized areas with low catalyst concentration, where the reaction might be slower or incomplete. Additionally, proper mixing helps in avoiding the formation of emulsions or phase separation, which can impede the reaction progress. In

summary, selecting an appropriate mixing intensity, such as a mechanical stirrer, for the esterification and transesterification processes in biodiesel production is essential to achieve a higher conversion rate, improve reaction efficiency, and obtain a higher yield of biodiesel (Sharma et al., 2011). It ensures uniformity in the reaction and enhances the overall performance of the process.

5.4 Coconut Biodiesel Properties Analysis

When compared to the minerals diesel and COCO, High heating value analysis reveals that CB has the lowest calorific value. Because of the high oxygen content and more thorough burning in CB, the source of thermal energy within the substance is reduced. This is due to the declining amounts of carbon and hydrogen.

According to a density investigation, the amount of CB that was produced had a density of 873 kg/m3, which was higher than mineral diesel and lower than COCO. Because the density of the produced biodiesel fits within the range of the biodiesel standard DIN EN 14214, which is between 860 and 900 kg/m^3, it is recognized as being comparable to pure mineral diesel.

According to the results of the flash point analysis, CB has a flash point of 110 °C, which is higher than mineral diesel but lower than COCO. This demonstrates that, in comparison to mineral diesel, CB generated is both cheap and safe for storage and transportation.

5.5 Diesel Engine Performance by Using Coconut Biodiesel Blends

The best blend ratio for CB, according to the data collected after the engine test, is B20 since it has the best mechanical efficiency, the most braking horsepower, and the lowest

fuel consumption rate of all the CB blends. B20 is the best alternative to pure diesel because it exhibits traits that are similar to those of mineral diesel.

5.6 Recommendations

Recommendations for further improvements in future are stated below.

1. Extraction of crude coconut oil using mechanical expeller to get pure crude oil.

2. The COCO should be stored and handled properly to prevent increase of the FFA value due to presence of moisture and oxidation.

3. Producing own catalyst which is heterogeneous catalyst to save time and cost. Heterogeneous catalyst reaction will give immediate effect compared to homogeneous catalyst and it is reusable.

4. Catalyst used must be handled and stored properly to maintain the purity. The purity has big effect on getting an accurate result.

5. Washing biodiesel method should be refine and done practically to save water as well as to prevent loss of biodiesel yield during washing.

6. Engine test for each of the CB blends must be run more than three times to get a more accurate result.

5.7 Future Research

Today, biodiesel production is widely done from research all around the world. Research done is to enhance, upgrade or improve the quality as well as the biodiesel yield rate and making it as green diesel as possible for substitute to the mineral diesel.

The main concern in producing biodiesel is the production cost. In future, refine the optimum conditions on biodiesel production such as the methanol to oil ratio, catalyst to oil ratio and most importantly the reaction time. Not only we need to save the usage of material such as methanol, acid catalyst and the base catalyst, but also we need to save time in production of FAME. Minimizing the optimum factors for producing biodiesel in the commercial industry would be a very economical.

Other than that, researchers can conduct some experiments such as the flame test and the burning test to analyze the purity of the fuel. This will help in increasing the fuel properties analysis.

Emission tests are important as air pollution has become a very hot current issue that is concerned by all the people around the world. Thus, emission test should be done by using more and more accurate emission analysers. Engine testing parameters can also be added such as the Brake Thermal Efficiency (BTE), Brake Effective Power and also the thermal efficiency analysis.

REFERENCES

Abbaszaadeh, A., Ghobadian, B., Omidkhah, M. R., & Najafi, G. (2012). Current biodiesel production technologies: A comparative review. *Energy Conversion and Management*, *63*, 138–148. https://doi.org/10.1016/j.enconman.2012.02.027.

Abdalla, I. E. (2018). Experimental studies for the thermo-physiochemical properties of Biodiesel and its blends and the performance of such fuels in a Compression Ignition Engine. *Fuel*, *212*, 638–655. https://doi.org/10.1016/j.fuel.2017.10.064.

Aburto, J., Román, S., González, A. R., & Vázquez, M. (2019). Biodiesel production from crude coconut oil using alkali-catalyzed transesterification. *Journal of Environmental Management*, *249*, 109340. doi:10.1016/j.jenvman.2019.109340.

Aditiya, H. B., Theofany, H. C., & Yheni, M. (2019). High-pressurizing green algae in third generation bioethanol production. *Journal of Physics: Conference Series*, *1402*(4). https://doi.org/10.1088/1742-6596/1402/4/044045.

Aghbashlo, M., Peng, W., Tabatabaei, M., Kalogirou, S. A., Soltanian, S., Hosseinzadeh-Bandbafha, H., Mahian, O., & Lam, S. S. (2021). Machine learning technology in biodiesel research: A review. *Progress in Energy and Combustion Science*, *85*, 100904. https://doi.org/10.1016/j.pecs.2021.100904.

Akhihiero, E. T., Oghenejoboh, K. M., & Umukoro, P. O. (2013). Effects of Process Variables on Transesterification Reaction of Jatropha Curcas Seed Oil for the Production of Biodiesel. *International Journal of Emerging Technology and Advanced Engineering*, *3*(6), 388–393.

Ali, O. M., Mamat, R., Abdullah, N. R., & Abdullah, A. A. (2015). Analysis of blended fuel properties and engine performance with palm biodiesel-diesel blended fuel. *Renewable Energy*, *86*, 59–67. https://doi.org/10.1016/j.renene.2015.07.103.

Alptekin, E., & Canakci, M. (2010). Optimization of Biodiesel Production from Sunflower Oil. *Energy Conversion and Management, 51*(7), 1378-1384.

Al-Zuhair, S., Al-Fadel, B., Al-Salem, S., & Daud, W. R. (2015). Optimization of biodiesel production process from crude Jatropha oil using artificial neural network modeling. *Journal of Cleaner Production, 86*, 478-483. doi:10.1016/j.jclepro.2014.08.045.

American Standards for Testing of Materials. (2014). *ASTM D974-14* Standard Test Method for Acid and Base Number by Color-Indicator Titration. West Conshohocken, PA: ASTM.

Ashraful, A. M., Masjuki, H. H., Kalam, M. A., Rizwanul Fattah, I. M., Imtenan, S., Shahir, S. A., & Mobarak, H. M. (2014). Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: A review. *Energy Conversion and Management*, *80*, 202–228. https://doi.org/10.1016/j.enconman.2014.01.037.

Atadashi, I. M., Aroua, M. K., & Abdul Aziz, A. R. (2011). The effects of filtration process on the production of biodiesel from crude palm oil. *Fuel, 90*(11), 3335-3338. doi:10.1016/j.fuel.2011.06.044.

Awolu, O. O., & Layokun, S. K. (2013). Optimization of two-step transesterification production of biodiesel from neem (Azadirachta indica) oil. *International Journal of Energy and Environmental Engineering*, *4*(1), 39. https://doi.org/10.1186/2251-6832-4-39.

Aydın, S. (2020). Comprehensive analysis of combustion, performance and emissions of power generator diesel engine fueled with different source of biodiesel blends. *Energy*, *205*, 118074. https://doi.org/10.1016/j.energy.2020.118074.

Ayetor, G. K., Sunnu, A., & Parbey, J. (2015). Effect of biodiesel production parameters on

viscosity and yield of methyl esters: Jatropha curcas, Elaeis guineensis and Cocos nucifera. *Alexandria Engineering Journal*, *54*(4), 1285–1290. https://doi.org/10.1016/j.aej.2015.09.011.

Bambase, M. E., Almazan, R. A. R., Demafelis, R. B., Sobremisana, M. J., & Dizon, L. S. H. (2021). Biodiesel production from refined coconut oil using hydroxide-impregnated calcium oxide by cosolvent method. *Renewable Energy*, *163*, 571–578. https://doi.org/10.1016/j.renene.2020.08.115.

Baskar, G., Aberna Ebenezer Selvakumari, I., & Aiswarya, R. (2018). Biodiesel production from castor oil using heterogeneous Ni doped ZnO nanocatalyst. *Bioresource Technology*, *250*, 793–798. https://doi.org/10.1016/j.biortech.2017.12.010.

Bello, E. I., Adekanbi, I. T., & Akinbode, F. O. (2015). Production and Characterization of Coconut (Cocos Nucifera) Oil and Its Methyl Ester. *European Journal of Engineering and Technology*, *3*(3), 25–35. www.idpublications.org.

Bibin, C., Gopinath, S., Aravindraj, R., Devaraj, A., Gokula Krishnan, S., & Jeevaananthan, J. K. S. (2020). The production of biodiesel from castor oil as a potential feedstock and its usage in compression ignition Engine: A comprehensive review. *Materials Today: Proceedings*, *33*, 84–92. https://doi.org/10.1016/j.matpr.2020.03.205.

Boey, P.-L., Maniam, G. P., & Hamid, S. A. (2011). Performance of calcium oxide as a heterogeneous catalyst in biodiesel production: A review. *Chemical Engineering Journal*, *168*(1), 15–22. https://doi.org/10.1016/j.cej.2011.01.009.

Boonmee, K., Chuntranuluck, S., Punsuvon, V., & Silayoi, P. (2010). Optimization of Biodiesel Production from Jatropha Oil (Jatropha curcas L.) using Response Surface Methodology. *Kasetsart J. (Nat. Sci.)*, *44*, 290–299.

Bouaid, A., Boulifi, N. El, Martinez, M., & Aracil, J. (2012). Optimization of a two-step

process for biodiesel production from Jatropha curcas crude oil. *International Journal of Low-Carbon Technologies*, *7*(4), 331–337. https://doi.org/10.1093/ijlct/ctr047.

British Standard Institution. (2010). *Bs En 14214:2008+a1:2009 Automotive fuels — Fatty acid methyl esters (FAME) for diesel engines — Requirements and test methods.* London: BSI.

Buasri, A., Chaiyut, N., Loryuenyong, V., Worawanitchaphong, P., & Trongyong, S. (2013). Calcium oxide derived from waste shells of mussel, cockle, and scallop as the heterogeneous catalyst for biodiesel production. *The Scientific World Journal*, *2013*. https://doi.org/10.1155/2013/460923.

Buyukkaya, E. (2010). Effects of biodiesel on a di diesel engine performance, emission and combustion characteristics. *Fuel*, *89*(10), 3099–3105. https://doi.org/10.1016/j.fuel.2010.05.034.

Can, Ö. (2014). Combustion characteristics, performance and exhaust emissions of a diesel engine fueled with a waste cooking oil biodiesel mixture. *Energy Conversion and Management*, *87*(2014), 676–686. https://doi.org/10.1016/j.enconman.2014.07.066.

Chinnamma, M., Bhasker, S., Madhav, H., Devasia, R. M., Shashidharan, A., Pillai, B. C., & Thevannoor, P. (2015). Production of coconut methyl ester (CME) and glycerol from coconut (Cocos nucifera) oil and the functional feasibility of CME as biofuel in diesel engine. *Fuel*, *140*, 4–9. https://doi.org/10.1016/j.fuel.2014.09.057.

Chong, C. T., Loe, T. Y., Wong, K. Y., Ashokkumar, V., Lam, S. S., Chong, W. T., Borrion, A., Tian, B., & Ng, J. H. (2021). Biodiesel sustainability: The global impact of potential biodiesel production on the energy–water–food (EWF) nexus. *Environmental Technology and Innovation*, *22*, 101408. https://doi.org/10.1016/j.eti.2021.101408.

Dhar, A., & Agarwal, A. K. (2014). Effect of Karanja biodiesel blend on engine wear in a

diesel engine. *Fuel*, *134*, 81–89. https://doi.org/10.1016/j.fuel.2014.05.039.

Di Pietro, M. E., Mannu, A., & Mele, A. (2020). NMR determination of free fatty acids in vegetable oils. *Processes*, *8*(410). https://doi.org/10.3390/PR8040410.

Dinesha, P., & Mohanan, P. (2018). Combined effect of oxygen enrichment and exhaust gas recirculation on the performance and emissions of a diesel engine fueled with biofuel blends. *Biofuels*, *9*(1), 45–51. https://doi.org/10.1080/17597269.2016.1256551.

Demirbas, A. (2009). Progress and Recent Trends in Biodiesel Fuels. *Energy Conversion and Management*, *50*(1), 14-34. https://doi.org/10.1016/j.enconman.2008.09.001.

Chen, Y., Han, B., & Wang, F. (2019). Biodiesel Production from Waste Cooking Oil Using an Efficient Immobilized Lipase. *Bioresource Technology*, *101*(23), 9523-9581. https://doi.org/10.1016/j.jclepro.2019.119166.

Emiroğlu, A. O., Keskin, A., & Şen, M. (2018). Experimental investigation of the effects of turkey rendering fat biodiesel on combustion, performance and exhaust emissions of a diesel engine. *Fuel*, *216*, 266–273. https://doi.org/10.1016/j.fuel.2017.12.026.

Esmaeili, H., & Foroutan, R. (2018). Optimization of biodiesel production from goat tallow using alkaline catalysts and combining them with diesel. *Chemistry and Chemical Technology*, *12*(1), 120–126. https://doi.org/10.23939/chcht12.01.120.

Espinoza, A., Bautista, S., Narváez, P. C., Alfaro, M., & Camargo, M. (2017). Sustainability assessment to support governmental biodiesel policy in Colombia: A system dynamics model. *Journal of Cleaner Production*, *141*, 1145–1163. https://doi.org/10.1016/j.jclepro.2016.09.168.

Farobie, O., & Matsumura, Y. (2017). State of the art of biodiesel production under supercritical conditions. *Progress in Energy and Combustion Science*, *63*, 173–203. https://doi.org/10.1016/j.pecs.2017.08.001.

Farooq, M., & Ramli, A. (2015). Biodiesel production from low FFA waste cooking oil using heterogeneous catalyst derived from chicken bones. *Renewable Energy*, *76*, 362–368. https://doi.org/10.1016/j.renene.2014.11.042.

Fattah, I. M. R., Masjuki, H. H., Kalam, M. A., Mofijur, M., & Abedin, M. J. (2014). Effect of antioxidant on the performance and emission characteristics of a diesel engine fueled with palm biodiesel blends. *Energy Conversion and Management*, *79*, 265–272. https://doi.org/10.1016/j.enconman.2013.12.024.

Fattah, I. M. R., Ong, H. C., Mahlia, T. M. I., Mofijur, M., Silitonga, A. S., Ashrafur Rahman, S. M., & Ahmad, A. (2020). State of the Art of Catalysts for Biodiesel Production. *Frontiers in Energy Research*, *8*(June), 1–17. https://doi.org/10.3389/fenrg.2020.00101.

Fukuda, H., Kondo, A., & Noda, H. (2001). Biodiesel Fuel Production by Transesterification of Oils. *Journal of Bioscience and Bioengineering*, *92*(5), 405-416.

Gebremariam, S. N., & Marchetti, J. M. (2018). Economics of biodiesel production: Review. *Energy Conversion and Management*, *168*(May), 74–84. https://doi.org/10.1016/j.enconman.2018.05.002.

Ghorbani, A., Bazooyar, B., Shariati, A., Jokar, S. M., Ajami, H., & Naderi, A. (2011). A comparative study of combustion performance and emission of biodiesel blends and diesel in an experimental boiler. *Applied Energy*, *88*(12), 4725–4732. https://doi.org/10.1016/j.apenergy.2011.06.016.

Goyal, P., Sharma, M. P., & Jain, S. (2013). Optimization of transesterification of Jatropha curcas oil to biodiesel using response surface methodology and its adulteration with kerosene. *Journal of Materials and Environmental Science*, *4*(2), 277–284.

Habibullah, M., Rizwanul Fattah, I. M., Masjuki, H. H., & Kalam, M. A. (2015). Effects of palm-coconut biodiesel blends on the performance and emission of a single-cylinder

diesel engine. *Energy and Fuels*, *29*(2), 734–743. https://doi.org/10.1021/ef502495n.

Hasan, M. M., & Rahman, M. M. (2017). Performance and emission characteristics of biodiesel–diesel blend and environmental and economic impacts of biodiesel production: A review. *Renewable and Sustainable Energy Reviews*, *74*(February), 938–948. https://doi.org/10.1016/j.rser.2017.03.045.

Hernández-Cruz, M. C., Meza-Gordillo, R., Torrestiana-Sánchez, B., Rosales-Quintero, A., Ventura-Canseco, L. M. C., & Castañón-Gonzáles, J. H. (2016). Chicken fat and biodiesel viscosity modification with additives for the formulation of biolubricants. *Fuel*, *198*, 42–48. https://doi.org/10.1016/j.fuel.2016.12.039.

Hossain, M. A., Chowdhury, S. M., Rekhu, Y., Faraz, K. S., & Islam, M. U. (2012). Biodiesel from coconut oil: a renewable alternative fuel for diesel engine. *World Academy of Science, Engineering and Technology*, *68*(8), 1289–1293.

Islam, S., Ahmed, A. S., Islam, A., Aziz, S. A., Xian, L. C., & Mridha, M. (2014). Castor Biodiesel. *Journal of Chemistry*, *2014*, 1–8. https://doi.org/10.1155/2014/451526

IEA. (2021). Global Energy Review 2021. International Energy Agency, France.

Kabir, I., Yacob, M., & Radam, A. (2014). Households' Awareness, Attitudes and Practices Regarding Waste Cooking Oil Recycling in Petaling, Malaysia. *IOSR Journal of Environmental Science, Toxicology and Food Technology*, *8*(10), 45–51. https://doi.org/10.9790/2402-081034551.

Kalam, M. A., Masjuki, H. H., Jayed, M. H., & Liaquat, A. M. (2011). Emission and performance characteristics of an indirect ignition diesel engine fuelled with waste cooking oil. *Energy*, *36*(1), 397–402. https://doi.org/10.1016/j.energy.2010.10.026.

Kasirajan, R. (2021). Biodiesel production by two step process from an energy source of Chrysophyllum albidum oil using homogeneous catalyst. *South African Journal of*

Chemical Engineering, *37*, 161–166. https://doi.org/10.1016/j.sajce.2021.05.011.

Kegl, B. (2011). Influence of biodiesel on engine combustion and emission characteristics. *Applied Energy*, *88*(5), 1803–1812. https://doi.org/10.1016/j.apenergy.2010.12.007.

Koh, M. Y., & Tinia, T. I. (2011). A review of biodiesel production from Jatropha curcas L. oil. *Renewable and Sustainable Energy Reviews*, *15*(5), 2240–2251. https://doi.org/10.1016/j.rser.2011.02.013.

Knothe, G. (2010). Biodiesel and renewable diesel: A comparison. Progress in Energy and Combustion Science, 36(3), 364-373.

Kumar, A., Kim, D., Omidvarborna, H., & Kuppili, S. K. (2014). *Combustion Chemistry of Biodiesel for the Use in Urban Transport Buses : Experiment and Modeling*., California : Mineta National Transit Research Consortium.

Kumar, G., Kumar, D., Singh, S., Kothari, S., Bhatt, S., & Singh, C. P. (2010). Continuous low cost transesterification process for the production of coconut biodiesel. *Energies*, *3*(1), 43–56. https://doi.org/10.3390/en3010043.

Kumar, K. J. S., & Raju, A. N. (2021). Performance and Emission Characteristics of Compressed Ignition Engine by Using Non-edible Coconut Biodiesel. *Lecture Notes in Mechanical Engineering*, *January*, 663–671. https://doi.org/10.1007/978-981-15-4308-1_52.

Kumar, P., Sharma, M. P., & Dwivedi, G. (2015). Impact of ternary blends of biodiesel on diesel engine performance. *Egyptian Journal of Petroleum*, *25*(2), 255–261. https://doi.org/10.1016/j.ejpe.2015.06.010.

Liaquat, A. M., Masjuki, H. H., Kalam, M. A., Fattah, I. M. R., Hazrat, M. A., Varman, M., Mofijur, M., & Shahabuddin, M. (2013). Effect of coconut biodiesel blended fuels on engine performance and emission characteristics. *Procedia Engineering*, *56*, 583–590.

https://doi.org/10.1016/j.proeng.2013.03.163.

Ling, J. S. J., Tan, Y. H., Mubarak, N. M., Kansedo, J., Saptoro, A., & Nolasco-Hipolito, C. (2019). A review of heterogeneous calcium oxide based catalyst from waste for biodiesel synthesis. *SN Applied Sciences*, *1*(8). https://doi.org/10.1007/s42452-019-0843-3.

Llamas, A., García-Martínez, M. J., Al-Lal, A. M., Canoira, L., & Lapuerta, M. (2012). Biokerosene from coconut and palm kernel oils: Production and properties of their blends with fossil kerosene. *Fuel*, *102*, 483–490. https://doi.org/10.1016/j.fuel.2012.06.108.

Lugo-Méndez, H., Sánchez-Domínguez, M., Sales-Cruz, M., Olivares-Hernández, R., Lugo-Leyte, R., & Torres-Aldaco, A. (2021). Synthesis of biodiesel from coconut oil and characterization of its blends. *Fuel*, *295*(December), 1200595. https://doi.org/10.1016/j.fuel.2021.120595.

Mahesh, S. E., Ramanathan, A., Begum, K. M. M. S., & Narayanan, A. (2015). Biodiesel production from waste cooking oil using KBr impregnated CaO as catalyst. *Energy Conversion and Management*, *91*, 442–450. https://doi.org/10.1016/j.enconman.2014.12.031.

Mahlia, T. M. I., Syazmi, Z. A. H. S., Mofijur, M., Abas, A. E. P., Bilad, M. R., Ong, H. C., & Silitonga, A. S. (2020). Patent landscape review on biodiesel production: Technology updates. *Renewable and Sustainable Energy Reviews*, *118*(April), 109526. https://doi.org/10.1016/j.rser.2019.109526.

Mahmudul, H. M., Hagos, F. Y., Mamat, R., Adam, A. A., Ishak, W. F. W., & Alenezi, R. (2017). Production, characterization and performance of biodiesel as an alternative fuel in diesel engines – A review. *Renewable and Sustainable Energy Reviews*, *72*(April),

497–509. https://doi.org/10.1016/j.rser.2017.01.001.

Malik, M. S. A., Mohamad Shaiful, A. I., Mohd Ismail, M. S., Mohd Jaafar, M. N., & Sahar, A. M. (2017). Combustion and emission characteristics of coconut-based biodiesel in a liquid fuel burner. *Energies*, *10*(4), 1–12. https://doi.org/10.3390/en10040458.

Man, X. J., Cheung, C. S., Ning, Z., Wei, L., & Huang, Z. H. (2016). Influence of engine load and speed on regulated and unregulated emissions of a diesel engine fueled with diesel fuel blended with waste cooking oil biodiesel. *Fuel*, *180*, 41–49. https://doi.org/10.1016/j.fuel.2016.04.007.

Marina, A. M., Che Man, Y. B., & Amin, I. (2009). Virgin Coconut Oil: Emerging Functional Food Oil. Trends in Food Science & Technology, 20(10), 481-487.

Martinot, E., & Sawin, J. L. (2009). *Renewables: Global Status Report: 2007. Renewable Energy Policy Network for the 21st Century*. [PDF] Available at : //www. ren21. net/pdf/RE2007_Global_Status_Report. pdf [Accessed on 21st February 2022].

Marchetti, J. M., Miguel, V. U., Errazu, A. F., & Marchetti, J. M. (2007). Possible methods for biodiesel production. *Renewable and Sustainable Energy Reviews*, *11*(6), 1300-1311.

Mašek, O. (2016). Biochar in thermal and thermochemical biorefineries-production of biochar as a coproduct. *Handbook of Biofuels Production: Processes and Technologies: Second Edition*, 655–671. https://doi.org/10.1016/B978-0-08-100455-5.00021-7.

Mat Yasin, M. H., Mamat, R., Najafi, G., Ali, O. M., Yusop, A. F., & Ali, M. H. (2017). Potentials of palm oil as new feedstock oil for a global alternative fuel: A review. *Renewable and Sustainable Energy Reviews*, *79*(May), 1034–1049. https://doi.org/10.1016/j.rser.2017.05.186.

Meher, L. C., Vidya Sagar, D., & Naik, S. N. (2006). Technical aspects of biodiesel

production by transesterification - A review. *Renewable and Sustainable Energy Reviews*, *10*(3), 248–268. https://doi.org/10.1016/j.rser.2004.09.002.

Mittelbach, M., & Remschmidt, C. (2004). *Biodiesel: The comprehensive handbook*, Austria : Martin Mittelbach.

Mofijur, M. ;, Masjuki, H. H., Kalam, M. A., Atabani, A. E., Fattah, I. M. R., & Mobarak, H. M. (2014). Comparative evaluation of performance and emission characteristics of Moringa oleifera and Palm oil based biodiesel in a diesel engine. *Industrial Crops and Products*, *53*, 78–84. https://doi.org/10.1016/j.indcrop.2013.12.011.

Mofijur, M., Masjuki, H. H., Kalam, M. A., & Atabani, A. E. (2013). Evaluation of biodiesel blending, engine performance and emissions characteristics of Jatropha curcas methyl ester: Malaysian perspective. *Energy*, *55*, 879–887. https://doi.org/10.1016/j.energy.2013.02.059.

Mofijur, M., Masjuki, H. H., Kalam, M. A., Atabani, A. E., Arbab, M. I., Cheng, S. F., & Gouk, S. W. (2014). Properties and use of Moringa oleifera biodiesel and diesel fuel blends in a multi-cylinder diesel engine. *Energy Conversion and Management*, *82*, 169–176. https://doi.org/10.1016/j.enconman.2014.02.073.

Mohiddin, M. N. Bin, Tan, Y. H., Seow, Y. X., Kansedo, J., Mubarak, N. M., Abdullah, M. O., Chan, Y. S., & Khalid, M. (2021). Evaluation on feedstock, technologies, catalyst and reactor for sustainable biodiesel production: A review. *Journal of Industrial and Engineering Chemistry*, *98*, 60–81. https://doi.org/10.1016/j.jiec.2021.03.036.

Mumtaz, M. W., Hamid, A., Arshad, M. S., & Adnan, A. S. (2011). An Insight into the Brimming Potential of Coconut Oil as an Economically Viable Source for Biodiesel - A Review. *Journal of Environmental Management*, *92*(4), 1339-1345.

Najafi, G. (2018). Diesel engine combustion characteristics using nano-particles in

biodiesel-diesel blends. *Fuel*, *212*(July 2017), 668–678. https://doi.org/10.1016/j.fuel.2017.10.001.

Nagarajan, V., & Gunasekaran, M. (2018). Optimization of biodiesel production from crude rubber seed oil using activated eggshell catalyst in a continuous packed-bed reactor. *Energy Conversion and Management*, *167*, 275-285. doi:10.1016/j.enconman.2018.04.019.

Nakpong, P., & Wootthikanokkhan, S. (2010). High free fatty acid coconut oil as a potential feedstock for biodiesel production in Thailand. *Renewable Energy*, *35*(8), 1682–1687. https://doi.org/10.1016/j.renene.2009.12.004.

Nalgundwar, A., Paul, B., & Sharma, S. K. (2016). Comparison of performance and emissions characteristics of di CI engine fueled with dual biodiesel blends of palm and jatropha. *Fuel*, *173*(January), 172–179. https://doi.org/10.1016/j.fuel.2016.01.022.

Nevin, K. G., & Rajamohan, T. (2004). Beneficial Effects of Virgin Coconut Oil on Lipid Parameters and In Vitro LDL Oxidation. *Clinical Biochemistry*, *37*(9), 830-835.

Ong, H. C., Milano, J., Silitonga, A. S., Hassan, M. H., Shamsuddin, A. H., Wang, C. T., Indra Mahlia, T. M., Siswantoro, J., Kusumo, F., & Sutrisno, J. (2019). Biodiesel production from Calophyllum inophyllum-Ceiba pentandra oil mixture: Optimization and characterization. *Journal of Cleaner Production*, *219*, 183–198. https://doi.org/10.1016/j.jclepro.2019.02.048.

Opoku-Boahen, Y., Azumah, S., Apanyin, S., Novick, B. D., & Wubah, D. (2012). The quality and infrared determination of trans-fatty acid contents in some edible vegetable oils. *African Journal of Food Science and Technology*, *3*(6), 142–148.

Özçelik, A. E., Aydoɨan, H., & Acaroɨlu, M. (2015). Determining the performance, emission and combustion properties of camelina biodiesel blends. *Energy Conversion and*

Management, *96*, 47–57. https://doi.org/10.1016/j.enconman.2015.02.024.

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. https://doi.org/10.1016/j.fuproc.2014.09.016.

Pathak, S. (2015). Acid catalyzed transesterification. *Journal of Chemical and Pharmaceutical Research*, *7*(3), 1780–1786. http://dx.doi.org/10.1016/j.fuproc.2015.01.005.

Paudel, S. R., Banjara, S. P., Choi, O. K., Park, K. Y., Kim, Y. M., & Lee, J. W. (2017). Pretreatment of agricultural biomass for anaerobic digestion: Current state and challenges. *Bioresource Technology*, *245*, 1194–1205. https://doi.org/10.1016/j.biortech.2017.08.182.

Pereira, R. G., Tulcan, O. E. P., Fellows, C. E., Da Silva, I. M., Do Espirito Santo Filho, D. M., De Jesus Lameira, V., & Quelhas, O. L. G. (2014). Energy generation using coconut biodiesel and coconut oil in a stationary engine. *International Journal of Oil, Gas and Coal Technology*, *7*(4), 450–453. https://doi.org/10.1504/IJOGCT.2014.062165.

Pullen, J., & Saeed, K. (2014). Factors affecting biodiesel engine performance and exhaust emissions - Part I: Review. *Energy*, *72*(March), 1–16. https://doi.org/10.1016/j.energy.2014.04.015.

Raghavan, K. (2010). *Biofuels From Coconuts*. *August 2010*. http://www.fact-foundation.com,[Accessed on 15 March 2022].

Raheem, I., Mohiddin, M. N. Bin, Tan, Y. H., Kansedo, J., Mubarak, N. M., Abdullah, M. O., & Ibrahim, M. L. (2020). A review on influence of reactor technologies and kinetic studies for biodiesel application. *Journal of Industrial and Engineering Chemistry*, *91*, 54–68. https://doi.org/10.1016/j.jiec.2020.08.024.

Rahman, M. M., Rasul, M. G., Hassan, N. M. S., Azad, A. K., & Uddin, M. N. (2017). Effect of small proportion of butanol additive on the performance, emission, and combustion of Australian native first- and second-generation biodiesel in a diesel engine. *Environmental Science and Pollution Research*, *24*(28), 22402–22413. https://doi.org/10.1007/s11356-017-9920-6.

Rao, K. S., Mutyalu, K. B., & Ramakrishna, A. (2015). International Journal of Modern Trends in Engineering and Research Diesel Engine Performance and Emission Characteristics with Chicken Fat Biodiesel Compared to other Biodiesels. *International Journal of Modern Trends in Engineering and Research*, *2*(7), 1638–1647.

Reddy, A. N. R., Ahamed, A. S., Islam, M. D., & Hamdan, S. (2015). Methanolysis of Crude Jatropha Oil using Heterogeneous Catalyst from the Seashells and Eggshells as Green Biodiesel. *ASEAN Journal on Science and Technology for Development*, *32*(1), 16–30. https://doi.org/10.29037/ajstd.9.

Reddy, A. N. R., Saleh, A. A., Islam, M. S., & Hamdan, S. (2017a). Active Razor Shell CaO Catalyst Synthesis for Jatropha Methyl Ester Production via Optimized Two-Step Transesterification. *Journal of Chemistry*, *2017*(1). https://doi.org/10.1155/2017/1489218

Reddy, A. N. R., Saleh, A. A., Islam, M. S., & Hamdan, S. (2017b). Optimization of transesterification parameters for optimal biodiesel yield from crude jatropha oil using a newly synthesized seashell catalyst. *Journal of Engineering Science and Technology*, *12*(10), 2723–2732.

Rochelle, D., & Najafi, H. (2019). A review of the effect of biodiesel on gas turbine emissions and performance. *Renewable and Sustainable Energy Reviews*, *105*(January), 129–137. https://doi.org/10.1016/j.rser.2019.01.056.

Saifuddin, N., Siti Fazlili, A., Kumaran, P., Pei-Jua, N., & Priathashini, P. (2016). The Production of Biodiesel and Bio-kerosene from Coconut Oil Using Microwave Assisted Reaction. *IOP Conference Series: Earth and Environmental Science*, *32*(1). https://doi.org/10.1088/1755-1315/32/1/012039.

Sajjadi, B., Houshfar, E., & Akia, M. (2013). A Review on Biodiesel Production Using Catalyzed Transesterification. *Renewable and Sustainable Energy Reviews, 22*, 466-473.

Sakthivel, R., Ramesh, K., Purnachandran, R., & Mohamed Shameer, P. (2018). A review on the properties, performance and emission aspects of the third generation biodiesels. *Renewable and Sustainable Energy Reviews*, *82*(November 2017), 2970–2992. https://doi.org/10.1016/j.rser.2017.10.037

Saluja, R. K., Kumar, V., & Sham, R. (2016). Stability of biodiesel – A review. *Renewable and Sustainable Energy Reviews*, *62*, 866–881. https://doi.org/10.1016/j.rser.2016.05.001

Samart, C., Sookkumnerd, T., & Krasae, P. (2013). Biodiesel production from crude palm oil by two-step heterogeneous acid/base catalyzed transesterification. *Energy Procedia, 34*, 182-187. doi:10.1016/j.egypro.2013.06.912.

Santos, E. (2012). Principales características de las materias primas utilizadas en la producción de biodiesel: la influencia del contenido y la concentración de los ácidos grasos. *Ingenium Revista de La Facultad de Ingeniería*, *13*(25), 53–61. https://doi.org/10.21500/01247492.1307.

Sharma, Y. C., Singh, B., & Upadhyay, S. N. (2011). Advancements in development and characterization of biodiesel: A review. *Fuel*, *90*(5), 1309-1324. doi:10.1016/j.fuel.2010.11.040.

Schmidt, J., & De Rosa, M. (2020). Certified palm oil reduces greenhouse gas emissions compared to non-certified. *Journal of Cleaner Production*, *277*. https://doi.org/10.1016/j.jclepro.2020.124045.

Shahir, V. K., Jawahar, C. P., Suresh, P. R., & Vinod, V. (2017). Experimental Investigation on Performance and Emission Characteristics of a Common Rail Direct InjectionEngine Using Animal Fat Biodiesel Blends. *Energy Procedia*, *117*, 283–290. https://doi.org/10.1016/j.egypro.2017.05.133.

Sharma, L., Grover, N. K., Bhardwaj, M., & Kaushal, I. (2012). Comparison of Engine Performance of Mixed Jatropha and Cottonseed Derived Biodiesel Blends with Conventional Diesel. *International Journal on Emerging Technologies*, *3*(1), 29–32.

Shohaimi, N. A. M., & Marodzi, F. N. S. (2018). Transesterifikasi sisa minyak masak dalam pengeluaran biodiesel menggunakan CaO/Al2O3 mangkin heterogenus. *Malaysian Journal of Analytical Sciences*, *22*(1), 157–165. https://doi.org/10.17576/mjas-2018-2201-20.

Silitonga, A. S., Masjuki, H. H., Mahlia, T. M. I., Ong, H. C., Atabani, A. E., & Chong, W. T. (2013). A global comparative review of biodiesel production from jatropha curcas using different homogeneous acid and alkaline catalysts: Study of physical and chemical properties. *Renewable and Sustainable Energy Reviews*, *24*, 514–533. https://doi.org/10.1016/j.rser.2013.03.044.

Silitonga, A. S., Masjuki, H. H., Mahlia, T. M. I., Ong, H. C., Chong, W. T., & Boosroh, M. H. (2013). Overview properties of biodiesel diesel blends from edible and non-edible feedstock. *Renewable and Sustainable Energy Reviews*, *22*, 346–360. https://doi.org/10.1016/j.rser.2013.01.055.

Silitonga, A. S., Masjuki, H. H., Mahlia, T. M. I., Ong, H. C., Kusumo, F., Aditiya, H. B., &

Ghazali, N. N. N. (2015). Schleichera oleosa L oil as feedstock for biodiesel production. *Fuel*, *156*, 63–70. https://doi.org/10.1016/j.fuel.2015.04.046.

Singh, R. K., & Padhi, S. K. (2006). Characterization of jatropha oil for the preparation of biodiesel. *Indian Journal of Natural Products and Resources*, *8*(2), 127–132.

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. https://doi.org/10.1016/j.rser.2009.07.017.

Singh Sikarwar, V., Zhao, M., Fennell, P. S., Shah, N., & Anthony, E. J. (2017). Progress in biofuel production from gasification. *Progress in Energy and Combustion Science*, *61*, 189–248. https://doi.org/10.1016/j.pecs.2017.04.001.

Sivakumar, M., Shanmuga Sundaram, N., Ramesh kumar, R., & Syed Thasthagir, M. H. (2018). Effect of aluminium oxide nanoparticles blended pongamia methyl ester on performance, combustion and emission characteristics of diesel engine. *Renewable Energy*, *116*, 518–526. https://doi.org/10.1016/j.renene.2017.10.002.

Subbarayan, M. R., Senthil Kumaar, J. S., & Anantha Padmanaban, M. R. (2016). Experimental investigation of evaporation rate and exhaust emissions of diesel engine fuelled with cotton seed methyl ester and its blend with petro-diesel. *Transportation Research Part D: Transport and Environment*, *48*, 369–377. https://doi.org/10.1016/j.trd.2016.08.024.

Sundus, F., Fazal, M. A., & Masjuki, H. H. (2017). Tribology with biodiesel : A study on enhancing biodiesel stability and its fuel properties. *Renewable and Sustainable Energy Reviews*, *70*(September 2015), 399–412. https://doi.org/10.1016/j.rser.2016.11.217.

Suresh, M., Jawahar, C. P., & Richard, A. (2018). A review on biodiesel production,

combustion, performance, and emission characteristics of non-edible oils in variable compression ratio diesel engine using biodiesel and its blends. *Renewable and Sustainable Energy Reviews*, *92*(April), 38–49. https://doi.org/10.1016/j.rser.2018.04.048.

Suresh, S., Sinha, D., & Murugavelh, S. (2016). Biodiesel production from waste cotton seed oil: engine performance and emission characteristics. *Biofuels*, *7*(6), 689–698. https://doi.org/10.1080/17597269.2016.1192442.

Suryanto, A., Suprapto, S., & Mahfud, M. (2015). The Production of Biofuels from Coconut Oil Using Microwave. *Modern Applied Science*, *9*(7), 93. https://doi.org/10.5539/mas.v9n7p93.

Suthisripok, T., & Semsamran, P. (2018). The impact of biodiesel B100 on a small agricultural diesel engine. *Tribology International*, *128*, 397–409. https://doi.org/10.1016/j.triboint.2018.07.042.

Swaroop, C., Jose, T. K., & Ramesh, A. (2016). Property Testing of Biodiesel Derived From Coconut Testa Oil and Its Property Comparison With Standard Values. *Technical Research Organisation India*, *2*(2),37-41.

Syed, A., Quadri, S. A. P., Rao, G. A. P., & Mohd, W. (2017). Experimental investigations on DI (direct injection) diesel engine operated on dual fuel mode with hydrogen and mahua oil methyl ester (MOME) as injected fuels and effects of injection opening pressure. *Applied Thermal Engineering*, *114*, 118–129. https://doi.org/10.1016/j.applthermaleng.2016.11.152.

Tan, P. qiang, Hu, Z. yuan, Lou, D. ming, & Li, Z. jun. (2012). Exhaust emissions from a light-duty diesel engine with Jatropha biodiesel fuel. *Energy*, *39*(1), 356–362. https://doi.org/10.1016/j.energy.2012.01.002.

Tan, Y. H., Abdullah, M. O., Kansedo, J., Mubarak, N. M., Chan, Y. S., & Nolasco-Hipolito, C. (2019). Biodiesel production from used cooking oil using green solid catalyst derived from calcined fusion waste chicken and fish bones. *Renewable Energy*, *139*, 696–706. https://doi.org/10.1016/j.renene.2019.02.110.

Tan, Y. H., Abdullah, M. O., & Nolasco-Hipolito, C. (2015). The potential of waste cooking oil-based biodiesel using heterogeneous catalyst derived from various calcined eggshells coupled with an emulsification technique: A review on the emission reduction and engine performance. *Renewable and Sustainable Energy Reviews*, *47*(July), 589–603. https://doi.org/10.1016/j.rser.2015.03.048.

Teixeira, E. C., Mattiuzi, C. D. P., Feltes, S., Wiegand, F., & Santana, E. R. R. (2012). Estimated atmospheric emissions from biodiesel and characterization of pollutants in the metropolitan area of Porto Alegre-RS. *Anais Da Academia Brasileira de Ciencias*, *84*(3), 655–667. https://doi.org/10.1590/S0001-37652012000300008.

Tiwari, S., Shrivastava, S., Verma, U., Arnold, R., Saxena, A., & Chaudhari, R. (2013). Prospects of Biodiesel production by Alkali-based transesterification from Jatropha curcas and waste oil. *International Journal of Pharmacy & Life Sciences*, *4*(11), 3093–3098.

Veza, I., Faizullizam Roslan, M., Farid Muhamad Said, M., & Abdul Latiff, Z. (2020). Improved performance, combustion and emissions of SI engine fuelled with butanol: A review. *International Journal of Automotive and Mechanical Engineering*, *17*(1), 7648–7666. https://doi.org/10.15282/IJAME.17.1.2020.13.0568.

Veza, I., Said, M. F. M., & Latiff, Z. A. (2021). Recent advances in butanol production by acetone-butanol-ethanol (ABE) fermentation. *Biomass and Bioenergy*, *144*(December 2020), 105919. https://doi.org/10.1016/j.biombioe.2020.105919.

Veza, I., Said, M. F. M., Latiff, Z. A., Roslan, M. F., & Azman Abas, M. (2021). Physico-chemical properties of Acetone-Butanol-Ethanol (ABE)-diesel blends: Blending strategies and mathematical correlations. *Fuel*, *286*(P2), 119467. https://doi.org/10.1016/j.fuel.2020.119467.

Wei, L., Cheng, R., Mao, H., Geng, P., Zhang, Y., & You, K. (2018). Combustion process and NOx emissions of a marine auxiliary diesel engine fuelled with waste cooking oil biodiesel blends. *Energy*, *144*, 73–80. https://doi.org/10.1016/j.energy.2017.12.012.

Woo, C., Kook, S., Hawkes, E. R., Rogers, P. L., & Marquis, C. (2016). Dependency of engine combustion on blending ratio variations of lipase-catalysed coconut oil biodiesel and petroleum diesel. *Fuel*, *169*, 146–157. https://doi.org/10.1016/j.fuel.2015.12.024.

Yang, J., Ahmed, A., & Hamdan, S. (2012). Production of Biodiesel From Waste Deep Frying Oils As a Renewable Energy Source. *Asian Journal of Science and Technology*, *4*(11), 54–57.

Yilmaz, N., Vigil, F. M., Benalil, K., Davis, S. M., & Calva, A. (2014). Effect of biodiesel-butanol fuel blends on emissions and performance characteristics of a diesel engine. *Fuel*, *135*, 46–50. https://doi.org/10.1016/j.fuel.2014.06.022.

Yogish, H., Chandrashekara, K., & Kumar, M. R. P. (2012). Optimization of experimental conditions for composite biodiesel production from transesterification of mixed oils of Jatropha and Pongamia. *Heat and Mass Transfer/Waerme- Und Stoffuebertragung*, *48*(11), 1955–1960. https://doi.org/10.1007/s00231-012-1034-6.

Yusoff, N. R. B. M., Hasan, S. bin H., & Abdullah, N. H. binti. (2013). Process to Produce Biodiesel Using Jatropha Curcas Oil (JCO). *International Journal of Materials Science and Engineering*, *1*(2), 100–103. https://doi.org/10.12720/ijmse.1.2.100-103.

Zhang, Y., Niu, S., Lu, C., Gong, Z., & Hu, X. (2020). Catalytic performance of NaAlO2/γ-

Al2O3 as heterogeneous nanocatalyst for biodiesel production: Optimization using response surface methodology. *Energy Conversion and Management*, *203*(August), 112263. https://doi.org/10.1016/j.enconman.2019.112263.