Batch Biodiesel Production by Esterification from Palm Fatty Acid Distillate with Microwave heating

Enarm Promnonsri

A Thesis Submitted in Fulfillment of the Requirements for the
Degree of Master of Engineering in Energy Technology
Prince of Songkla University
2022

Batch Biodiesel Production by Esterification from Palm Fatty Acid Distillate with Microwave heating

Enarm Promnonsri

A Thesis Submitted in Fulfillment of the Requirements for the

Degree of Master of Engineering in Energy Technology

Prince of Songkla University

2022

Thesis Title Batch biodiesel production by esterification from palm fatty acid distillate with microwave heating
Author Miss Enarm Promnonsri
Major Program Energy Technology

Major Advisor

....
(Asst. Prof. Dr. Saysunee Jumrat)

Co-advisor

....
(Asst. Prof. Dr. Yutthapong Pianroj)

....
(Asst. Prof. Dr. Teerasak Punvichai)

....
(Assoc. Prof. Dr.Theerayut Leevijit)

Examining Committee:

....Chairperson
(Asst. Prof. Dr. Arkom Palamanit)

....Committee
(Asst. Prof. Dr. Yutthapong Pianroj)

....Committee
(Asst. Prof. Dr. Saysunee Jumrat)

....Committee
(Asst. Prof. Dr. Boonya Charnnok)

....Committee
(Asst. Prof. Dr. Teerasak Punvichai)

....Committee
(Assoc. Prof. Dr. Theerayut Leevijit)

....Committee
(Dr. Sopida Sungsoontorn)

The Graduate School, Prince of Songkla University, has approved this thesis as fulfillment of the requirements for the Master of Engineering Degree in Energy Technology.

....
(Asst. Prof. Dr. Thakerng Wongsirichot)
Acting Dean of Graduate School

This is to certify that the work here submitted is the result of the candidate's own investigations. Due acknowledgement has been made of any assistance received.

....Signature
(Asst. Prof. Dr. Saysunee Jumrat)
Major Advisor

....Signature
(Asst. Prof. Dr. Yutthapong Pianroj)
Co-advisor

....Signature
(Asst. Prof. Dr. Teerasak Punvichai)
Co-advisor

....Signature
(Assoc. Prof. Dr. Theerayut Leevijit)
Co-advisor

....Signature
(Miss Enarm Promnonsri)
Candidate

I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

....Signature
(Miss Enarm Promnonsri)
Candidate

หัวข้อวิทยานิพนธ์ การผลิตไบโอดีเซลแบบครั้งด้วยปฏิกิริยาเอสเทอร์ริฟิเคชันจากส่วนกลั่นกรดไขมันปาล์มโดยใช้พลังงานความร้อนจากไมโครเวฟ
ผู้เขียน นางสาวเอ็นอาร์ม พรมโนนศรี
สาขาวิชา เทคโนโลยีพลังงาน
ปีการศึกษา 2565

บทคัดย่อ

การศึกษานี้แสดงให้เห็นถึงระบบการผลิตไบโอดีเซล (MWBD) โดยใช้พลังงานความร้อนจากคลื่นไมโครเวฟ โดยใช้แมกนีตรอนสองตัวที่มีกำลังไมโครเวฟรวม 1,270 วัตต์ วางแบบไม่สมมาตรบนด้านตรงกันข้ามของถังปฏิกรณ์ จะใช้ในการผลิตเมทิลเอสเทอร์จากส่วนกลั่นกรดไขมันปาล์ม (PFAD) โดยจะใช้ตัวเร่งปฏิกิริยาที่เป็นกรด (H_2SO_4) ที่ 2 %wt. หาสภาวะที่เหมาะสมในการผลิตไบโอดีเซลโดยใช้วิธีการตอบสนองพื้นผิวใช้การออกแบบการทดลองของ Box-Behnken เพื่อหาสภาวะที่เหมาะสมที่สุดโดยให้ได้ (%conversion) สูงสุดและที่ต้นทุนขั้นต่ำ (USD) ซึ่งอยู่ที่อัตราส่วนโมล PFAD ต่อ MeOH 1:9; อุณหภูมิในการทำปฏิกิริยา 80 องศาเซลเซียส, และเวลาในการทำปฏิกิริยา 20 นาที แบบจำลองการถดถอยทำนายการแปลง %conversion และต้นทุน (USD) ด้วยค่าสัมประสิทธิ์ของการกำหนด (R^2) ที่ 0.9519 และ 0.8654 ตามลำดับ และโปรไฟล์อุณหภูมิจากการจำลองเหมาะสมกับข้อมูลจากการทดลองจริงเกี่ยวกับอุณหภูมิที่วัดได้ภายในถังปฏิกรณ์ สุดท้ายได้ทำการวิเคราะห์คุณสมบัติของน้ำมันไบโอดีเซลจากคลื่นไมโครเวฟ (MWBD) ตามมาตราฐาน และเปรียบเทียบกับมาตรฐานเครื่องยนต์ดีเซลเพื่อการเกษตร (AED) และน้ำมันดีเซลหมุนเร็ว (HSD) ของไทย และได้ค่ามาตรฐานตามที่มาตราฐาน (AED, HSD และมาตราฐานกรมธุรกิจพลังงาน) กำหนด จากนั้นไบโอดีเซลจากคลื่นไมโครเวฟ (MWBD), น้ำมันดีเซลหมุนเร็วเชิงพาณิชย์ (CHSD), และ MWBD ผสมด้วย CHSD 50:50 โดยปริมาตร (เชื้อเพลิงเหลวที่ผสมแล้ว = LFB), ได้นำไปทำการการทดสอบในเครื่องยนต์ดีเซลที่มีช่วงกำลัง 1.28-5.09 กิโลวัตต์ ที่ความเร็วรอบคงที่ 2,200 รอบต่อนาที เชื้อเพลิงทั้งหมดดำเนินการคล้ายกับเชื้อเพลิงน้ำมันดีเซลหมุนเร็วเชิงพาณิชย์ (CHSD) ในการทดสอบและไม่พบปัญหาใดๆ ต่อเครื่องยนต์

Thesis Title Batch biodiesel production by esterification from palm fatty acid distillate with microwave heating
Author Miss Enarm Promnonsri
Major Program Energy Technology
Academic Year 2022

ABSTRACT

This study demonstrats a batch microwave-assisted biodiesel (MWBD) conversion system. It used two magnetrons with a 1,270 Watt total microwave (MW) power placed asymmetrically on opposite sides of the MW cavity. It was used to produce methyl ester from palm fatty acid distillate (PFAD) with 2 %wt. acid catalyst (H_2SO_4). The response surface method applied Box-Behnken experimental design to find the optimal point giving the maximal %free fatty acid (FFA) at the minimum cost (USD). This focused with the mol ratio of PFAD to MeOH as 1:9; reaction temperature at 80 °C; and reaction time for 20 min. The regression models predicted the %FFA conversion and the cost (USD) with coefficients of determination (R^2) of 0.9519 and 0.8654, respectively. Simulations with the finite element method (FEM) were also performed. The temperature profiles from simulations fit well the experimental data on measured temperature. Finally, the most important fuel properties of the MWBD were analyzed and compared with Thai agricultural engine diesel (AED) and high-speed diesel (HSD) standards, and the standards were satisfied. Then, the MWBD, the liquid fuel blend (LFB; MWBD: CHSD 50:50 by volume), and commercial high-speed diesel (CHSD) were tested in a diesel engine over the power range 1.28-5.09 kW at the fixed 2,200 rpm speed. All the fuels performed similar to the CHSD in the test and no problems were found in the runs of the engine.

ACKNOWLEDGEMENT

This thesis has been accomplished as intended because it has received help from many parties. The author thanks Asst. Prof. Dr. Saysunee Jumrat (major advisor), Asst. Prof. Dr. Yutthapong Pianroj, Asst. Prof. Dr. Teerasak Punvichai, Assoc. Prof. Dr. Theerayut Leevijit (co-advisor), who provide great assistance in all areas of knowledge and guides on how to solve problems. All thesis examination committees for taking the time to give advice of this thesis. Mr. Stit Promnonsri and Mrs. Rusda Promnonsri, the father and mother. The author would like to thank the family for the support and encouragement from friends Energy Technology Throughout all those who did not mention.

I greatly acknowledge financial assistance from the research grants by the National Research Council of Thailand under the Research University Network (RUN) project of the year 2016, also a research funding for the thesis of the year 2020 from Prince of Songkla University. Moreover, I thank Professor Dr. Sumet Chaiprapat and the 2020 Interdisciplinary Graduate School of Energy Systems (IGS-Energy) for supporting scholarships.

I wish to express my appreciation to the Energy Technology Department and the Faculty of Engineering for providing assistance and document coordination throughout the study period. I thank the Center for Science and Equipment at the Prince of Songkla University, Surat Thani Campus. Thank you, an engine laboratory Department of Mechanical Engineering and Department of Chemistry Engineering, Faculty of Engineering and Office of Scientific Instruments and Testing Prince of Songkla University, which provides advice and facilitates research and testing tools and science glassware, and New Biodiesel Company Limited for supporting the palm fatty acid distillate. Big thanks, Assoc. Prof. Dr. Theerayut Leevijit, Lecturer at the Department of Mechanical Engineering Faculty of Engineering Prince of Songkla University Hat Yai Campus, and Dr. Sopida Sungsoontorn, Lecturer at the Department of Mechanical Engineering Faculty of Engineering Rajamangala University of Technology Rattanakosin, who provided support in scientific instruments, engine and experiments supporting academic knowledge and big thanks, Dr. Suppakit Eiadtrong, Lecturer at the Faculty of Engineering and Technology,

Department of Mechanical Engineering and Robotics Walailak University, and Mr. Parinya Mompiboon to provide assistance and provide academic knowledge.

Finally, for those who benefit from this research. In addition, including the helpers and encouragement that are not mentioned until the researcher can finish the research. The researchers are extremely grateful and therefore thank you very much for this opportunity.

Enarm Promnonsri

CONTENTS

Contents **Page**

CONTENTS (CONTINUED)

Contents **Page**

CONTENTS (CONTINUED)

Contents **Page**

LIST OF TABLES

Tables **Page**

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF ABBREVIATIONS AND SYMBOLS

β	Heating rate
ε'	Dielectric constant
ε''	Dielectric loss factor
$v^{\cdot}$	Specific input fuel by volume
ρ	Fuel density
$m^{\cdot}$	Specific input fuel by mass
AED	Agricultural engine diesel
ASTM	American society for testing and materals
AV	Acid value
BHP	Brake horse power
BMEP	Brake mean effective pressure
BP	Brake power
BSFC	Brake specific fuel consumption
BT	Brake torque
BTE	Brake thermal efficiency
CO	Carbon monoxide
CO_2	Carbon dioxide
CHSD	Commercial high-speed diesel
C_{total}	Production cost
$C_{material}$	Raw material cost
C_{energy}	Energy cost
DG	Diglyceride
DI	Direct injection
FAAE	Fatty acid alkyl esters
FAME	Fatty acid methyl ester
FEM	Finite element method
FFA	Free fatty acid
HSD	High speed diesel
LFB	Liquid fuel blend
LHV	Low heating value
MAB	Microwave-assisted biodiesel
MG	Monoglyceride
MWBD	Microwave biodiesel
N	Engine speed
n_{bth}	Brake thermal efficiency
P	Brake power
PFAD	Palm fatty acid distillate

LIST OF ABBREVIATIONS AND SYMBOLS (CONTINUED

SIF	Specific input fuel
SO	Sulfur dioxide
SSR	Solid-state relay
TG	Triglyceride
TLC/FID	Thin layer chromatography/flame ionization detector
W	Brake torque

CHAPTER 1

INTRODUCTION

1.1 Background

Average daily fuel consumption in January 2022 increased by 20.9% compared to the same period last year, with the use of diesel fuel increasing by 24.4%. For high-speed diesel B7, the usage increased to 62.63 million liters/day (up 68.9%). Normally, Thai transportation and industry use diesel fuel mainly and diesel. It is usually produced from crude oil. Thailand had oil imports during January-May 2022 averaged at 1,000,569 barrels/day, an increase from the same period last year (an increase of 8.9%), with crude oil imports increasing to 937,101 barrels/day (an increase of 6.7%) in line with higher domestic demand. The value of crude oil imports increased to 98,388 million baht/month (an increase of 91.8%) due to the use of diesel fuel. It has a huge impact on the environment (Energy May 2022). The majority of this impacts are air pollution, which is the effect of fuel consumption. Because the combustion of fuel will cause various substances contaminated in the volatile oil and if the engine is incompletely combustion, it will cause soot and harmful gases such as carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and hydrocarbon gases causing global warming, resulting in global warming.

Thailand is a country with the potential for biodiesel production because there are many oil crops such as oil palm, coconut, soybean, and peanut, especially oil palm. Thailand has 13 biodiesel plants and a total biodiesel capacity of 6,618,600 L/day, which is mainly used for crude palm oil (CPO) and refined bleached deodorized palm oil raw material for production (Department of Energy Business, 2017), but CPO oil is an oil that must go through a refining process to obtain refined palm oil (RPO), which is an oil for consumption. If too much CPO oil is used as raw material for biodiesel production, it will cause the oil market to be scarce. Therefore, there has been a research study to find alternative plants that are not used for consumption, such as Jatropha oil. and castor oil, in addition, the Department of Energy Business has increased the use of B100 biodiesel blends in high-speed diesel from B5 to B7 in 2017 (Department of Energy Business,

2017) and According to the Renewable and Alternative Energy Development Plan 2015-2036, the production target is to increase biodiesel consumption to B10 in private vehicles and B20 in transport vehicles (Department of Alternative Energy Development and Efficiency, 2017).

Therefore, it is necessary to find alternative raw materials to meet the demand (Chen, Shan et al. 2015). This makes biodiesel an alternative to petroleum and fossil fuels because the price is cheaply made from natural materials and is also as efficient as diesel fuel biodiesel in Thailand, at present, the government has a policy to seriously encourage the production and use of biodiesel according to the announcement of the Department of Energy Business regarding the characteristics and quality of diesel fuel. Thailand has the third highest palm oil yield in the world according to the office of agricultural economics data showing the entire country's palm oil output for the year 2018 (Office of Agricultural Economics, 2018), equal to 15.5 million tons by the main plantation area of oil palm of Thailand is in the south the output is 13.9 million tons, accounting for 89.6% of the total production of the country. When considering three provinces in the southern part of Thailand: Chumphon, Surat Thani, and Krabi, the output from these provinces is 60.0% of the total output produced in the southern region. From this information, it can be seen that oil palm is an important economic crop. Causing many agricultural industries related to palm oil to start the crude palm oil production industry, which has information from the office of industrial economics. It has estimated the production capacity of crude palm oil in the country at 2.8 million tons per year continuing to the refining industry, the office of agricultural economics estimates a total production capacity of 2.5 million tons per year, and many other industries both in the manufacturing industry for consumption, including the consumer industry in daily life.

In the refining process of refined palm oil there will be a potential by-product that can be used as raw material for biodiesel production, namely palm fatty acid distillate (PFAD), whose PFAD is 5% of oil. Crude palm in 2016, Thailand had a total PFAD of 89,000 tons, which could be used as an alternative feedstock for biodiesel production. Because there is no issue of used for consumption or produce food and PFAD is used as raw material in soap manufacturing industry, and manufacturing industry grease etc.

PFAD is composed mainly of fatty acids. If free fatty acid (FFA) content is higher than 80 wt.%, it is necessary to reduce the amount of FFA in PFAD to biodiesel by esterification reaction to reduce free fatty acid. The problems of using PFAD as raw material for biodiesel production are the large amount of chemicals, low biodiesel purity, energy consumption and long reaction time (Abdul Kapor, Maniam et al. 2017). Typically conductive or convection heating which takes quite a long time to produce. Therefore, research is being undertaken to utilize the heat from microwave systems to reduce the time and space of biodiesel production. In this research, the process of heating from microwaves is used as a higher energy efficiency compared to general heat conventional heating, has good temperature distribution and can shorten the reaction time.

1.2 Research objectives

Biodiesel production from palm fatty acid distillate (PFAD) with the objectives of the experiment are as follows:

1) To study the optimum condition for the maximum yield of biodiesel production from methanol and PFAD.

2) To study the properties of the produced methyl ester from PFAD with microwave heating.

3) To analyze the performance of engine testing with produced biodiesel.
4) To analyze the cost of biodiesel producing.

1.3 Scope of research

Biodiesel production from palm fatty acid distillate (PFAD) was observed with the scope of the experiment as follows:

1) Observed the molar ratio of PFAD to methanol, reaction temperature, reaction time, and cost for biodiesel production from PFAD.

2) Studied the biodiesel production process of the PFAD with an esterification reaction in conjunction with the microwave-assisted biodiesel system.

3) Observed the properties and engine performance at the optimum of methyl esters produced from PFAD with esterification reaction by microwave heating.

4) Studied the cost of biodiesel producing from PFAD

1.4 Expected benefits

1) Know the best conditions in biodiesel production from PFAD with microwave heating.
2) Know the properties of biodiesel produced under optimal conditions from PFAD with microwave heating.
3) Get the product biodiesel from PFAD with microwave heating with the purity of methyl ester.
4) Know the cost of biodiesel production from PFAD with microwave heating.

CHAPTER 2

THEORETICAL BACKGROUND AND LITERATURE REVIEW

In an examination of documents related to this research, the main issues were to investigate the application of palm fatty acid distillate to produce biodiesel as a diesel alternative fuel as well as the results of the study on optimal conditions for biodiesel production, biodiesel properties, and engine performance testing on the test platform. In addition, there is also a document review of the study guideline on the biodiesel production process the details of the document verification are as follows.

2.1 Biofuel

Biofuel is a fuel from biomass, rather than by the very slow natural processes that is produced over a short time span caused by the formation of elements of fossil fuels such as oil. Biomass can be converted to fuel also known as biofuels. Bringing all forms of biomass or organic materials that are sources of natural energy such as organic waste, agricultural waste, and waste from industrial production processes such as fermentation, combustion, and gasification until it is heat or gas to be utilized or transformed into electrical energy.

Biofuel can be the greenhouse gas mitigation potential, emission comparable to fossil fuels in some scenarios to negative emissions in others.

The two most common types of biofuel are biodiesel and bioethanol. The energy content in the global production of bioethanol and biodiesel is 2.2 and 1.5 EJ per year, respectively.

Biofuels can be split up into three categories:

- Solid biofuel (wood pellets, fuelwood, wood residues, vegetal material, and animal waste)
- Liquid biofuel (biodiesel, and biogasoline)
- Biogase (from anaerobic fermentation and from thermal processes)

1) Solid State Biofuels It includes non-fossil organic matter of biological origin (biomass), which may be used as fuel to convert biomass to heat or electricity itself such as wood,

and agricultural wastes including trees and plants. They provide biomass in the form of firewood, sawdust, wood chips, charcoal, and plywood pellets that can be burned and given as heat.

2) Biogas consists mainly of carbon dioxide and methane, and these gases are produced by the decomposition of biomass in the absence of oxygen or by thermal processes from biomass, the main component is methane gas. Nowadays, it is popular to be packed in gas cylinders for household use.

3) Liquid biofuels includes all liquid fuels of natural origin such as biodiesel, methanol, ethanol, and butanol derived from the production of biomass or biodegradable waste suitable to be used as a mixture or as an alternative to liquid fuels from petroleum. Biomass can be converted directly into liquid fuels, is or biofuels to help meet transportation fuel needs. The two most common types of biofuels in use today are biodiesel and ethanol, represent.

2.1.1 Ethanol

Ethanol (CH_3CH_2OH) is a renewable fuel that can be made from various plant materials. It is a natural renewable fuel that is clear and colorless is produced from biomass both plants and animals such as corn, wheat, sorghum, and grass. Ethanol is an alcohol produced through the process of fermentation from bio high carbon mass can be used as fuel for cars and is used as an admixture with gasoline to increase octane and reduce carbon monoxide and smoke emissions.

Most ethanol is made from plant starches and sugars particularly corn which can use cellulose and hemicellulose contained in biomass which is an inedible fibrous material that makes up the majority of plants.

Methods for converting biomass into energy, such as ethanol, are obtained by fermentation which during fermentation, there will be microorganisms and will metabolize the sugar contained in plants and produce ethanol.

2.2 Biodiesel

Biodiesel is manufactured from plant oils such as soybean oil, and cooking or oils or animal fats (pork lard, and beef tallow). Biodiesel is a diesel replacement fuel for use in diesel engines.

Becouse biodiesel production use increase. Therefore, new raw materials must be developed that can be brought into the market, such as grease and algae. Because these raw materials are not enough to meet the demand. But it has great potential to complement the current feedstock supply.

Biodiesel is a liquid fuel often referred to as biodiesel in its pure or B100, unblended form unmixed as well as diesel biodiesel can be used as fuel for compression ignition engines.

Biodiesel performance in cold weather depends on the blend of biodiesel, depending on the raw materials used in production. In general, blends of biodiesel over oil work well and provide efficiency in cold temperatures. Usually, diesel fuel performs the same in cold climates. Both biodiesel and diesel there are some compounds that crystallize in winter climates as a result, fuel generators and suppliers are adding cold flow modifiers. for optimum performance in cold weather.

2.2.1 Definition and Meaning of Biodiesel

Biodiesel is an alternative fuel similar to conventional or ‘fossil’ is a liquid fuel derived from vegetable oils or animal fats with similar fuel properties to diesel fuel but with low sulfur content or no sulfur impurities, produced from straight vegetable oil, animal oil fat, tallow, and waste cooking oil it is classified as a clean fuel. It can be produced in many ways such as microemulsion, pyrolysis, hydrogenation, esterification, transesterification, etc. (Department of Alternative Energy Development and Efficiency, 2014) (Shahir, Jawahar et al. 2015, Ciolkosz 2020).

Biodiesel is a mixture of fatty acid alkyl esters obtained from ester exchange process of vegetable oils or animal fats. These lipid feedstocks are composed of diglycerides, monoglycerides, triglycerides, and free fatty acids 80–98 %wt. In the transesterification reaction basic or acid catalyst is normally used to enhance the reaction rate. (Gebremariam and Marchetti 2017, Shemelis Nigatu and Jorge Mario 2017).

Biodiesel and alternative diesel fuel as renewable energy have more interesting in energy due to environmental advantages and this product is made from renewable resources and the cost of biodiesel is still limited in bringing biological sources such as vegetable oils and animal fats are used as raw material, an adaption of continuous produce process and high quality glycerol from biodiesel by product (glycerol) it is biodegradable and non-toxic, has low emission and so is environmentally beneficial (Ma and Hanna 1999).

Biodiesel is a alternative energy is advantages for numerous reasons.

(1) Being renewable, it can sustain a continuous supply chain.

(2) The molecular structure of biodiesel oil is biodegradable. Less emissions from combustion

(3) Reduce the dependency on crude oil imports and can result in considerable improvement of a country economic potential.

(4) Compared to diesel, using biodiesel can help reduce black smoke, carbon monoxide (CO), and sulfur dioxide. In addition, the use of biodiesel in place of diesel fuel can reduce the life-cycle of carbon dioxide (CO_2), thereby reducing global warming.

(5) It can be used biodiesel as a substitute for diesel in boilers or internal combustion diesel engines without modifications.

(6) It contains more oxygen which aids the complete combustion of the fuel, leading to a decrease in emissions.

(7) It requires minor engine modification or use with modern diesel engines. It has good engine performance compared to gasoline.

(8) It has properties good lubricity; therefore, it will reduce the wear of metal parts, making the engine last longer (Karmakar and Halder 2019).

2.2.2 Biodiesel production

Biodiesel is produced by the reaction of vegetable oils or animal fats with alcohol (methanol, ethanol, and propyl alcohol) and an acid or base catalyst (sodium hydroxide or potassium hydroxide), sulfuric and hydrochloric acids are also used in the production of biodiesel (Marchetti et al., 2017).

Biodiesel can be produced from various raw materials or biomass such as vegetable oils, animal fats, leftover vegetable oils and food crops. Biodiesel is generally produced through a combination of processes. The process depends on the composition of the raw materials used in production. which the reaction of vegetable oil with alcohol (mostly methanol, ethanol, and isopropyl alcohol) to methyl esters, ethyl esters, and glycerol by using an appropriate catalyst. Therefore, the research and development of efficient catalysts with superior activities are critical and imperative for biodiesel production. In general, acid or base chemical catalysis, are the most common process in biodiesel production (Chozhavendhan, Vijay Pradhap Singh et al. 2020, and Karmakar and Halder 2019). Biodiesel, an alternative fuel for diesel engines, is non-toxic biodegradable, and renewable. Biodiesel can also be prepared by the esterification of free fatty acids present in animal fats, with methanol over acid catalysts and can also be prepared by transesterification of triglyceride with alcohol (Hidayat, Rochmadi et al. 2015).

2.2.3 Reaction for biodiesel production

Biodiesel production is a chemical process, although it is started from the same free fatty acid in the raw material the manufacturing process may vary even though esterification can produce biodiesel but in commercial terms, the process is used as a transesterification. The reaction consists of suitable catalyst oils or fats and low molecular weight alcohol, typically methanol or ethanol (Marchetti et al., 2017).

This is due to the decreasing amount of oil reserves and the detrimental environmental impacts on the environment such as exhaust gases, and incomplete combustion. Biodiesel has gained attention in the field of renewable fuels, and renewable fuels environmentally friendly can be recycled and biodegradable currently, it is produced through the process alkali conversion and catalytic addition with methanol. This results in a reduction in reaction time. However, the products used to produce oil such as vegetable oils that react with alcohol must be waterless and the content of free fatty acids must be low, because both will cause the oil production reaction to form soap (Vasudevan and Briggs 2008).

1) Transesterification reaction of triglycerides

It is an intermolecular reaction of triglycerides in which the main constituents of vegetable oils, animal fats, and alcohol are produced, get products and glycerin. The molar ratio of alcohol to triglycerides in relative quantities is 3 to 1, and then, moderation is used to allow the reaction to go on the right-hand side. Methyl ester and glycerin have obtained the birth of glycerin, a methyl ester incompatible substance. This caused the reaction to go more on the right-hand side and had a higher triglyceride conversion factor. The transesterification is composed of a reversible reaction in 3 steps, respectively, Triglycerides are converted to diglycerides, the diglycerides were converted to monoglycerides, and finally, it becomes glycerin, with each step using 1 mole of methanol. Therefore, for the reversible reaction toward the methyl ester product, a sufficient amount of methanol must be added to the reaction (Marchetti et al., 2017).

This equation is a simplified form of the following transesterification reaction.

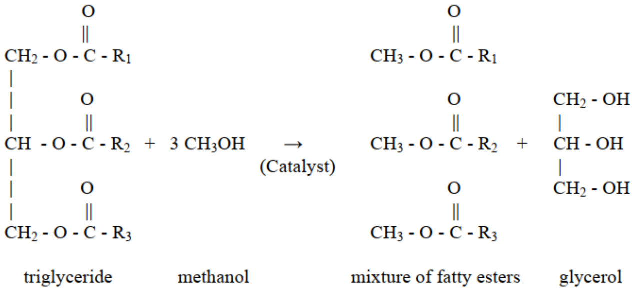


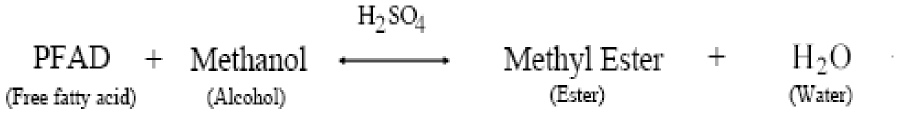
Figure 2.1 Transesterification reaction

(Lucena, Silva et al. 2008)

2) Esterification reaction of free fatty acid

The esterification reaction is an acid-and-alcohol reaction in a catalyst to become an ester. Sulfuric acid is commonly used as an esterification catalyst and is a reversible reaction, so must. The water was extracted and the reaction proceeded to the right to increase the ester yield. Esterification reaction is carried out using a catalyst such as sulfuric acid in order to form the "green process", different catalysts have several important advantages, such as less toxicity, less corrosion, and less toxicity and fewer environmental problems. The esterification with a solid acid catalyst, including acid zeolites, ion-exchange resins, sulfonic acid-modified mesostructured silica, tungsten oxide zirconia (Hidayat, Rochmadi et al. 2015). Esterification reaction in which free fatty acids react with methanol in the presence of acid as a catalyst. The product is methyl ester and water by the mechanism of the esterification process of free fatty acids with a catalyst first step, the acid-formed protonation. The dislodged proton produces oxonium ions. The addition of methanol is more than enough. The balance of the reaction toward the esterification product becomes more complete (Marchetti et al., 2017).

The esterification reaction is a balanced reaction. that will result in the highest yield of methyl ester It depends on the factor of the initial alcohol to FFA ratio, and the process temperature. mostly as the reaction progresses, the product is water and methyl esters are formed until the end point is reached. The yield of methyl ester can be increased if there is water in the process during the esterification reaction. The dewatering can be done by using selective sorbents for water adsorption or by heating methods beyond the dewatering point. (Lucena, Silva et al. 2008).



$$\underset{\text{(Free fatty acid)}}{\text{PFAD}} + \underset{\text{(Alcohol)}}{\text{Methanol}} \xleftrightarrow{H_2SO_4} \underset{\text{(Ester)}}{\text{Methyl Ester}} + \underset{\text{(Water)}}{H_2O}$$

Figure 2.2 Esterification reaction

There are several factors affecting the esterification and catalysis process, including the methanol to oil ratio, temperature, time, concentration, type of catalyst, and stirring as the following details.

2.1) The ratio between methanol to oil

There are several types of catalytic alcohol such as methanol, ethanol, propanol, butanol, and ethyl alcohol. Methanol and ethanol are used both in research and industrial applications. Which can be reproduced and environmentally friendly therefore, ethanol is a good choice for fuel production. The advantages of butanol are it can be better mixed with raw fat. In addition, using large molecules of alcohol has a higher boiling point than using small alcohol molecules allowing it to work at high temperatures but using moderate pressure butanol gave the highest reaction rate, followed by 1-propanol and ethanol, respectively. Although methanol catalysis gave the slowest reaction rate, two factors affect the compatibility of reactants in the reaction adding non-polarity and the reaction temperature due to the increase in the molecular weight of the alcohol. Theoretically, it has been found that 3 moles of methanol per triglyceride are required 1 mol to obtain 3 mol of methyl sterol and 1 mol of glycerol means a 3:1 methanol to oil ratio is required 6:1 ratio of oil will produce the most product. The higher the alcohol content, the faster the reaction and the more esters will be formed but the reaction was incomplete when the methanol to oil ratio was higher than the methanol to oil ratio of 6:1. It also made the separation between the ester layer and the water layer difficult. It takes longer and costs more to split for the used oil, it was found that a 7:1 ratio of methanol to oil is required to obtain the most esters more than using pure oil this may be because the used oil has a higher viscosity, requiring a large amount of methanol to dissolve the oil and causing the oil methanol contact. The amount of catalyst and the methanol to oil ratio have a greater effect than the temperature and time, although the use of different alcohol led to differences in reaction mechanism and ester content (Meher, Dharmagadda et al. 2006).

2.2) Temperature

Temperature is an important factor in biodiesel production, using high temperatures in the reaction speed up the reaction rate, with high temperatures reducing the separation of the individual phases. The reaction rate constant increases and increases the compatibility of reactants and catalysts and decreases reaction time but the use of high temperature causes the product to be reduced accordingly. In addition, using high temperatures will produce more soap for pure oil in used oils, high temperatures will increase the viscosity of the biodiesel and have a soapy effect and result in a reduction in the product. Improved solubility of oil in methanol and increased contact area resulted in higher triglycerides. It makes the reaction good and fast but has the effect of accelerating the soap formation as well. This shows that high temperature hurts pure oil but it has a positive effect on used oil because it makes it very viscous. The temperature used is related to the time used. Temperatures above the boiling point of alcohol should be avoided as high temperatures catalyze the soapy reaction of the glycerides (Meher, Dharmagadda et al. 2006).

2.3) Time

The time required to complete the transesterification reaction is related to the reaction temperature, at high temperatures. The amount of time it takes will be less but if using low temperature, the longer it takes for the reaction to complete, the longer it will take for the reaction mechanism, it was found that if it took 15 minutes for the reaction to occur. The reaction is rapid during the first 5 minutes, forming 90% of the ester, then the reaction is slow until complete birth at 15 minutes, and if allowed to elapse until with in 15-30 minutes. The resulting ester does not increase but it will reduce the product that occurs due to a large amount of time and will cause the ester hydrolysis to reduce the amount of ester fatty are added and eventually soap is formed. Over time, more soaps will begin to be seen. Therefore, it must be controlled not to take too long as it will accelerate the reverse reaction. This results in a decrease in the product, but the concentration of methyl ester increases with increasing time, this is because it increases the precursor mix and the dispersion of methanol in the oil (Attanatho, Magmee et al. 2004).

2.4) Concentration and type of catalyst

If the catalyst concentration is too low, it will not be enough to catalyze the reaction but if too much will cause less product because the soap is created instead of increasing the viscosity of the solution methyl ester concentration increased with increasing catalyst concentration due to the mass transfer of methanol to oil ratio. However, using a high methanol to oil ratio will increase the contact of methanol and oil more, thereby increasing the concentration of methyl ester as well. However, the excessive addition of methanol will cause additional esters and will interfere with stratification between methyl ester and glycerin as methanol improves the solubility of both layers. In addition, reduced product formation increases solubility at elevated temperatures. This reduces the separation between methyl ester and glycerin. The reaction rate using the catalyst increases with the use of more acid content. However, the use of too much acid stimulates the ether from the alcohol degradation reaction to much alkali will cause triglycerides to turn into soap. The more alkaline, the more triglycerides turn into soap. This leads to less conversion to esters, for example, the reduction of the product when the sodium hydroxide concentration is increased from 0.5 to 1.5 due to soap formation in the reaction. The soap formation causes the methyl ester to dissolve in the glycerol layer. This makes it more difficult to separate the methyl ester layer and the glycerol layer. It also results in excessive catalyst separation and costly soap removal. The concentration of the catalyst has a greater effect than the temperature reaction time and the ratio of methanol to the oil used (Attanatho, Magmee et al. 2004).

2.2.4 Feedstocks of biodiesel production

Biodiesel can be made from biomass, such as vegetable oil that is popular and not edible. (Sani, 2012, and Gebremariam, 2018). Most of these feedstocks are highly productive in the production of biodiesel due to the high content of fatty acids and triglycerides (Gnanaprakasam, 2013).

1) Edible oil

Most or all of the oil that can be consumed or produced comes from plant resources. They are mostly used for direct consumption (Bhuiya, 2014). The extraction of oil for use in human consumption is obtained from natural resources without any chemical processes. Raw materials or oils that are commonly used in biodiesel production, the majority are palm oil, peanut oil, soybean, and sunflower (Pragya, 2013).

1.1) Palm oil

Palm oil is an important oil used for consumption, up to 70%-90% of palm oil.Most palm oil is used in the food industry and the remainder is used in industrial applications (Karmakar, 2010). Palm oil 1.25 liter can produce biodiesel 1 liter (Riazi, 2017). Palm oil is extracted from palm kernels. The oil content is as high as 20-21% wt (Sumathi, 2008). But it must be treated with palm oil before reacting and after treating palm oil free fatty acids are reduced to about 0.1%. The largest producers of palm oil are Malaysia and Indonesia.

1.2) Soybean oil

Soybean oil is a raw material for consumption because there are many benefits in the field of nutrition. Mainly produced in Brazil, East Asia, and the USA, soybean oil production is 222 million tons, and the majority of biodiesel production is produced in the USA 1.3 liters of soybean oil can produce up to 1 liter of biodiesel (Karmakar, 2010).

1.3) Rapeseed oil

Rap or Canola is a flower that can be found throughout Europe and Canada, mostly used as animal feed. Rapeseed oil has a high yield as rapeseed oil can be produced into biodiesel at a 1:1 liter ratio (Demirbas, 2007).

. 2) Non edible oil

Non-edible oil that cannot be consumed is oil that cannot be used as human food and can run alive because it is harmful to health or unhygienic and it is mainly used in industries such as the chemical industry, the soap industry, and biofuels. The obstacle of using non-edible oil as a raw material for biodiesel production is the high content of FFA that reacts with the catalyst to form soap as a result, the yield of biodiesel is reduced. Therefore, raw materials used in the production of biodiesel with a high content of FFA must be used to reduce the amount of FFA before transesterification (Baskar, 2016).

2.1) Jatropha oil

Jatropha oil is extracted from Jatropha seeds. It is commonly planted in climates with high temperatures and polluted water. Therefore, it is found in Egypt as a source of biodiesel. It is also the main source of biodiesel in Africa, and Asia. Jatropha seed oil contains 30-35 wt.% oil and can be used to produce biodiesel. Jatropha oil is mainly used in cosmetics, soap industry, and lubricants (Atadashi, 2012).

2.2) Castor oil

It is a plant that has a high demand in the world market. To be used in various industries such as the pharmaceutical industry, thereby causing insufficient quantities for the production of biodiesel. Biodiesel made from castor oil has a cloudy and low flow point. On the other hand, some properties such as the viscosity of biodiesel from castor oil are not within the international standards of biodiesel fuels (Demirbas, 2016).

2.3) Waste oil (Used cooking oil)

Used vegetable oil is another raw material that has the potential to be used to produce biodiesel. due to its low price compared to other raw materials It is also a raw material that each country can produce by itself in large quantities. In addition, the properties of biodiesel produced from used vegetable oils are similar to biodiesel from other types of vegetable oils. Used cassava to produce energy is also a suitable choice (Acquaye, 2012).

2.4) Animal fat

The use of animal fats is a promising trend for biodiesel production. This is because in some countries the use of animal fat is prohibited in animal feed, such as in the USA and Europe. In which animal fat has a high viscosity can harden easily at room temperature and has poor vaporization characteristics because it contains a lot of saturated fatty acids. Fat is in the form of fat from beef or mutton and is mainly composed of triglycerides. Animal tallow is another good alternative to biodiesel production because it is a cheap raw material or in some areas may be a waste that is not popular for consumption. This is because animal fat is a worthless raw material for the commercial food industry (Thamsiriroj, 2011).

2.5) Algae oil

Algae is also a raw material that can be used to produce biodiesel. In general in algae have oil content of 20%-80% which can be converted into various types of fuel such as biodiesel and kerosene. Algae contains essential oils such as good fatty acids. and can be used as raw material for biodiesel production (Milledge, 2013). Table 2.1 the difference between edible and non-edible raw materials (Bhosle, 2005).

Table 2.1 Differences between edible oil and non-edible oil (Demirbas, 2016).

	Edible oil	**Non edible oil**
Source	Vegetable sources	Vegetable oils
Use	Necessary consumption, such as being consumed as food for energy	It is mainly used in chemical factories such as detergent production, soap production, and fuel.
Composition	Vegetable oils have a positive effect on health and nutrition.	Oils that cannot be consumed due to their negative effects on health.
Oil extraction	Oil extraction does not use chemicals used in the extraction.	Oil extraction requires the use of chemicals to extract it.
Price	High	Low
Example	Such as: soybeans, rapeseed, canola, coconut, groundnut, oat, and sorghum	Such as: almond, jatropha, curcus, palm, rice bran, sesame, and salmon oil

2.2.5 Reactant

1) Fat or oil

Choosing a fat or oil to use in biodiesel production must take into account process chemistry decisions and economic decisions. Chemical process The raw material difference between fat and oil selection is the amount of FFA in relation to triglycerides.

2) Alcohol

The most commonly used alcohols in biodiesel production are methanol, ethanol, and isopropanol but the main factor and quality of alcohol is that it must be anhydrous. The presence of water results in a low productivity of the biodiesel reaction and a high content of soap, free fatty acids, and triglycerides. When glycerin and palm ethyl ester are separated. The excess alcohol phase is separated from the oil body. It is eliminated by evaporation (Malvade and Satpute 2013).

2.2.6 Catalyst

The production of biodiesel has a high production cost. It is an obstacle to use in terms of alternatives to diesel fuel. For this reason, alternatives to reduce the cost of biodiesel production are being studied. One way to reduce the cost of biodiesel production may come from different technologies with the same raw material Some technologies may have an economic effect with reduced energy consumption. and can reduce costs. Similarly, this economical advantage may be because of the relative minimum cost of the feedstock involved like a catalyst (Athar and Zaidi 2020).

Catalysts can be bases, acids, or enzymes. The most commonly used catalysts for biodiesel production are sodium hydroxide, potassium hydroxide, and sodium methoxide. Most of them use vegetable oil as the main raw material in production. If vegetable oil is crude oil. There will be a component small amounts of free fatty acids which, if the amount of free fatty acids will cause during the reaction to form soap and crude glycerin.

The catalyst is hygroscopic. and will form water when dissolving in the alcohol precursor can also absorb water from the air during storage. If excessive water absorption occurs will result in the catalyst not working well and will cause the biodiesel to have properties that do not meet the standards. Alkaline catalysts are the most economical option for biodiesel production.

Acid esterification systems have been used for a long time. To be used to reduce fatty acids to methyl esters resulting in yields above 99% and flushing water from the system at the same time. This is because the starting material and mixture of acid and methanol move in opposite directions. The acid esterification system produces a product or by product water.

In batch system the water accumulates in the reactor tank to the point where the reaction can be stopped prematurely. The use of sulfuric acid tends to migrate into the water, leaving methanol making it unable to react acid esterification systems therefore require water management methods (Marchetti et al.,2017).

Results from fuel use due to the rapidly developing economy, the energy demand has increased. Therefore, the amount of oil imports has increased every year. In addition to the high cost of fuel imports from abroad, there are problems with fuel consumption both in terms of reduced volumes and the pollution caused by its use and production. Surveys of fossil energy sources have shown that the energy available today has been reduced and gone. Therefore, alternative energy sources must be found to replace them, taking into account two principles: clean energy should be used without harming the environment both in the production process and in the process of use or have very little impact on the environment another is that it is a sustainable or renewable energy source. One of the solutions found is to take oils from known plants or animals and use them for consumption, such as soybean oil, palm oil, coconut oil, lard, etc. Research and experiments have shown that some plants can provide oil but cannot be edible, such as oil from castor seeds and Jatropha seed oil because there are toxic substances that can be used to produce fuel.

Gasohol (E85) is gasohol blended with up to 85% denatured ethanol with conventional benzene. It is an environmentally friendly fuel because the emissions from the exhaust are very little compared to gasoline. It is widely used in Brazil, Sweden, and America. The results of the experiment with gasohol engines found that it was able to reduce the amount of carbon monoxide and hydrocarbon compounds from exhaust emissions.

Biodiesel uses vegetable oils instead of fuel in an attempt to find renewable energy from the everdepleting petroleum based fuel. One-way scientists devised and experimented with how many plants can provide oil and can be used, for example, used to paint houses, make medicines, and cosmetics, and can also be used as fuel or lubricants. Oil plants such as soybeans, peanuts, coconuts, sesame, castor, sunflower seeds, and sugar cane, are plants for starch and sugar. These plants, when decomposed and put through the extraction process, will produce ethanol. Each plant used to produce biodiesel produces biodiesel with different properties. For example, biodiesel derived from soybean oil produces biodiesel with high phosphorus. Phosphorus must be kept as low as the specified threshold by using pure soybean oil. From studying the environmental impact of diesel and biodiesel use as fuel found that the exhaust from the engine was used. Biodiesel is less polluting than diesel fuel except that the amount of nitrogen gas produced will be higher than the amount of substance released as shown in Table 2.2.

Table 2.2 Comparison of results of using 100% biodiesel and 20% biodiesel blend. Information from: Renewable Energy, House of Representatives Energy Committee (Eiadtrong, Maliwan et al. 2021).

Exhaust pollution	**Biodiesel 100%**	**Biodiesel 20%**
Carbon Monoxide	Decrease 43.2%	Decrease 12.6%
Hydrocarbon	Decrease 56.3%	Decrease 11.0%
Dust	Decrease 55.4%	Decrease 18.0%
Nitrogen oxide	Increased 5.8%	Increased 1.2%
Carcinogen	80-90%	Decrease 20%

The use of biodiesel can solve the problem of air pollution caused by engine combustion because biodiesel from plants reduces the amount of gas that causes the greenhouse effect. In addition, biodiesel production from used vegetable oils can be recooked or used to produce animal feed because used vegetable oil contains dioxin, which is a carcinogen. When ingested, it can be dangerous.

With the use of biodiesel in engines, there is a caution that the engine power is lower than the normal diesel fuel by 3%. Biodiesel vehicles there will be more frequent maintenance intervals than diesel fuel.

2.2.7 Neutralizer

Neutralizers are used to remove base or acidic catalysts from biodiesel oil and glycerol byproducts. If you use a base catalyst neutralizers are often used to obtain acids and if cleaning biodiesel able to add neutralizing agent. Although various acids are common alternatives to neutralize basic or neutral catalysts, as mentioned earlier

2.2.8 Fatty acid methyl esters

Fatty acid methyl esters (FAME) are organic esters composed of one ester group (monoester) is synthesized by either the esterification of fatty acids with methanol or the transesterification of triglycerides with methanol, the molecular formula R-COO-CH_3, where R is the chain fatty acid straight-chain hydrocarbons are the main constituents of biodiesel. Its fuel properties are similar to those of petroleum diesel but the combustion produces cleaner exhaust as it does not contain sulfur and aromatics, has good engine lubrication properties, and is biodegradable (Department of Alternative Energy Development and Efficiency, 2014).

2.2.9 Free fatty acids

Free fatty acids (FFA) are organic acids separated from triglycerides in vegetable oils or animal fats by hydrolysis of triglycerides with acid bases or enzymes. The catalyst in combination with weak acidic heating of free fatty acids increased the acid value of vegetable oils and accelerated the oxidation of vegetable oils. Saturated will quickly oxidize and go rancid (Department of Alternative Energy Development and Efficiency, 2014).

2.2.10 Acid value

Acid value (AV) is the quality specification of vegetable oils or animal waxes for biodiesel production and biodiesel properties requirements. The acid value indicates the acid content. In oil as either free fatty acid content or acid, a catalyst is obtained by titration with a solution of potassium hydroxide according to ASTM D664 or EN 14104 test method. Values are expressed in milligrams of potassium hydroxide per gram of oil (Department of Alternative Energy Development and Efficiency, 2014).

2.2.11 Advantages of biodiesel

The use of biodiesel as a replacement for diesel derived from fossil fuels have both environmental and engine performance advantages.

1) Environment

Using biodiesel can reduce emissions of global warming greenhouse gases such as carbon dioxide (CO_2), sulfur dioxide (SO), and carbon monoxide (CO) are generated by combustion in engines. This is due to complete combustion due to approximately 10-12% oxygen (O) (Ciolkosz, 2015, Yasin et al., 2017) by the National Biodiesel Board and the Environmental Protection Agency (US Environmental Agency) of the United States, experimenting with different biodiesel formulas with diesel engines, found that biodiesel B100 formula can reduce CO_2 emissions by 78% and B20 formula biodiesel can reduce CO_2 emissions equal to 15.66% and the Naval Shipyard Department has experimented with biodiesel with a 145 hp diesel engine, found that it can reduce smoke from combustion equal to 50%, reduce CO_2 gas equal to 78%, reduce SO gas equal to 99%. Reduce CO gas by 20% and reduce dust by 39% (King Mongkut's University of Technology Thonburi, 2002, Research and Development Institute for Alternative Energy from Palm Oil and Oil Plants, 2007).

2) Engine performance

Because biodiesel has similar properties to diesel, it can be used interchangeably without engine modifications and improves combustion efficiency air and oil are evenly distributed and biodiesel has a cetane number in the range of 60-70, which is higher than that of diesel, reducing ignition delay. (Mat Yasin, Mamat et al. 2017, Ciolkosz 2020). Research and Technology Institute of PTT Public Company Limited experimented with mixing biodiesel from used vegetable oil and coconut oil in the amount of 1-2% and found that it can increase the lubrication index for diesel fuel up to 2 times, thereby reducing the wear of parts in the engine (King Mongkut's University of Technology Thonburi, 2002).

3) Economic and national security

(1) Help farmers in the country by increasing the value of crops and creating jobs creating an energy market to support agricultural produce left over from consumption.

(2) Biodiesel is a fuel that can be produced from crops in the country thus saving foreign currency in importing crude oil from abroad, thereby enhancing the country's stability and energy stability. Reduce the impact of the energy crisis which has a high impact on the country's economy.

4) Domestic fuel production

Thailand has a share of diesel fuel consumption much higher than gasoline. The diesel market in Thailand is worth twice as much as gasoline and in the future, there is a tendency that refineries may not to produce enough diesel for domestic use. Therefore, the use of biodiesel reduces the imbalance in the production of refineries.

5) Disadvantages of biodiesel

Biodiesel has a heating value (HV) than diesel fuel approximately 10%, resulting in lower speed and power of biodiesel engines than diesel engines. Biodiesel has cloudiness and pours points. Its high volatility and volatile capacity are therefore unsuitable for use in extremely cold regions (Mat Yasin, Mamat et al. 2017, Ciolkosz 2020). Oxides (NO) are higher than in diesel engines (Surat Thani palm oil research center, 2017). Therefore, these disadvantages of biodiesel can be solved by mixing it with diesel in a different ratio (Energy Policy and Planning Office, 2002).

2.2.12 Benefits of biodiesel

Biodiesel is a fuel that has many benefits over diesel fuel and has properties that do not cause an impact on the environment. The main benefit of biodiesel is that the fuel does not produce carbon dioxide (CO_2). This is caused by the fact that when oil plants are grown, they absorb the same amount of CO_2 as they emit. When the fuel burns causing complete combustion. Fertilizer production is not the only source of pollution associated with biodiesel production but there are also other sources such as esterification, solvent extraction of the oil, drying, refining, and transportation. All these processes require a new energy input. in the form of electricity or form of fuel and both of these forms contribute to greenhouse gas emissions. In assessing the impact from various sources a specific technique known as life cycle analysis is required. Biodiesel is rapidly biodegradable and completely non-toxic. This means that oil spills are much less risky than fossil diesel spills. Will consider our section analysis on LCA. Biodiesel has a higher flash point property than diesel fuel. So it is safer in case of collision.

Biodiesel is regarded as a new and clean alternative fuel that can be used to replace diesel fuel. However, biodiesel also has some advantages and disadvantages.

The advantages of using biodiesel are as follows:

- It is a biodegradable resource, environmentally friendly, non-toxic, and recyclable.

- It can reduce the amount of emissions that cause the greenhouse effect and reduce SO_2, CO_2, CO, HC and PM emissions.
- Production of biodiesel, has a simpler process than the production of diesel.
- The country's energy security will be increased, energy dependency will be reduced, and the use of fossil fuels can be reduced.
- Biodiesel is more economical because it can be produced from biomass. and domestic production.
- Biodiesel has a high flash point. which makes the safer fuel.
- It does not need engine modification to use B20 oil.

On the other hand, the disadvantages of using biodiesel are as follows:

- It has higher NOx emissions than diesel.
- Higher pour points and clouds are not available in countries with cold climates.
- Corrosive to copper and brass due to biomass used for production.
- Slightly higher viscosity compared to diesel fuel.

2.2.13 Biodiesel properties

Biodiesel derived from vegetable oils or animal fats containing longn chain alkyl constituents of methyl, ethyl, and propyl esters. To bring the waste cooking oil through the process by choosing to be the main raw material in the production of biodiesel. Therefore, the variance in raw material quality is quite important. For example, the quality of biodiesel must be controlled during production in order to meet the required standards (Wong, Ng et al. 2019). Biodiesel produced under microwave heating conditions was tested for fuel properties such as higher heating value, specific gravity, viscosity, pour point, flash point, condensing temperature distillation 90% recovered, sulfur content, carbon content, copper strip corrosion water content, and dirty sludge was tested at the Petroleum Science and Technology Research Center of Thailand according to the ASTM standard.

The properties of biodiesel fuel produced will have different properties depending on the raw materials used in production. These properties are important in quality control either in the petroleum based fuels industry or otherwise. The parameters that determine the quality of biodiesel can be divided into two groups. One group includes key parameters such as density, flash point, viscosity, escape point and cetane, which are used for mineral oil based fuels and another group will explain specifically chemical composition and purity of fatty acid esters such as monoglycerides, diglycerides, triglycerides.

Phasinam,Nikhomchaiprasert et al. 2021 studied biodiesel production according to ISO 15550-2002: International combustion engine designation and engine power measurement method (IS BGS, 2002). It is a general engine performance testing standard applicable to almost all types of internal combustion engines including small-medium boat engines (Marine Craft up to 24 m Hull Length; ISO 8665). Torque (Engine brake torque) and fuel consumption at various engine speeds and quality of combustion exhaust of the engine, such as smoke, exhaust gas, emissions, and exhaust gas temperature, respectively all measured data were used for comparative analysis and displayed in the form of engine performance according to international standards.

2.3 Biodiesel production reactor

Biodiesel production reactors can generally be divided into five categories: shift reactors, continuous flow reactors, ultrasonic reactors, and supercritical reactors.

1) Batch reactor

The batch reactor is a widely used industrial reactor from Figure 2.3. The working principle of the shift reactor is that the reactants are placed in the reaction tank and mixed so that the reaction is complete for a specified time, and the products are removed from the reaction tank for processing. The next step is that most shift reactors use a stirring tank and a motorized stirring system. The advantage is that it can be adapted to the production of various types of products due to the simple principle of operation. Losses during operation or supervision reactions are easy, the duration of each operation can be set evenly, and production costs are low. High labor and different quality products due to one-on-one production (He and Gerpen 2015).

Figure 2.3 Biodiesel batch processor

(He and Gerpen 2015)

2) Continuous reactor

Continuous reactor the principle of operation is that all reactants are continuously fed at the reactor inlet and the resulting product is also continuously flowed out at the reactor outlet. The reactor base is always at the same temperature and concentration, with the most popular continuous reactor used in biodiesel production being the continuous stirred tank reactor (CSTR). The CSTR reactor is similar to the stirred tank reactor. Instead, they are designed to be serialized or multi-layered and a continuous flow system is added as shown in Figure 2.4. The continuous reactor is a high capacity suitable for commercial production, consistent product quality, and reduced production costs (He and Gerpen 2015).

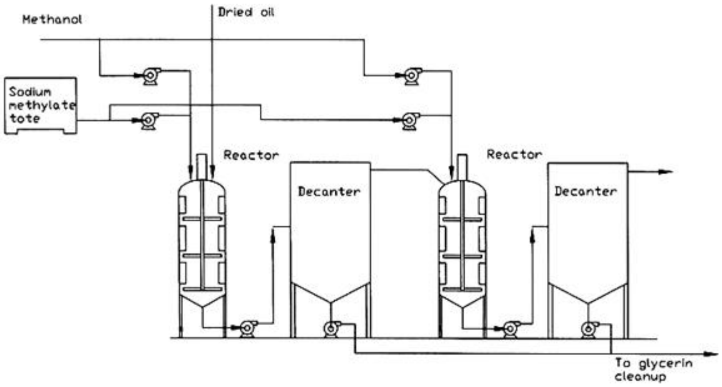


Figure 2.4 Continuous-flow biodiesel reactor – a two-step process

(He and Gerpen 2015)

3) Ultrasonic reactor

An ultrasonic reactor is a useful device for mixing immiscible liquids such as vegetable oils or animal fats with alcohol, which causes intense mixing so that the reaction can proceed. Achieve faster through the transfer of energy to the liquid to produce air bubbles and bubble collapse due to acoustic cavitation. Biodiesel is similar to the case of shift reactors but it took much less time (He and Gerpen 2015).

4) Supercritical reactors

Supercritical reactor production of biodiesel and after the reaction must be washed but sometimes problems can arise so conventional cells need to use a catalyst to induce a catalyst removal reaction to obtain pure biodiesel, avoiding the use of a catalyst can be a critical process. Extremely with the use of high temperature and pressure, typically at 300 °C and a pressure of 40 MPa or higher, the vegetable oil or animal fat must be mixed with alcohol to form the same phase, then the reaction takes place in fast duration without catalyst but it has a high production cost due to the need for high temperature and pressure.

2.4 Oil palm

It an edible vegetable oil that comes from the fruit of oil palm trees, also known as Elaeis guineensis. Two types of oil can be produced; crude palm oil comes from squeezing and the palm kernel part comes from grinding.

Palm oil is the main ingredient used in nearly 50% of products from chocolate, pizza, donuts and chocolate to toothpaste, shampoo and lipstick. It is also used as animal feed and as a biofuel in industrial plants.

Palm oil it is semi-solid at room temperature and is also resistant to oxidation. This makes it possible to use with products resulting in a longer shelf life. Stable at high temperatures.

Oil palm is also a very efficient crop a large quantity of oil can be produced in a small area throughout the year. This makes it attractive for growers and smallholders to be able to secure palm oil.

Palm oil is a very effective plant. It produces more oil per area than other plants or biomass. There are also farmers who are dependent on palm oil production for their livelihood.

Figure 2.5 Oil palm (Nakorn 2005)

Elias guineensis is a cross between dura, which has a thick shell, a large seed with a mesocarp of 30-50% by weight and oil content of 17-18%, and tenera, which is a medium-heavy-shelled species. The pulp is 60-90% of the weight and the oil content is 22-24%. The pulp of the medium-sized oil palm is a bunch, the exocarp and the middle layer (mesocarp) consisting of tissue. The fat which is then produced is called crude palm oil (CPO). Total fat is approximately 73.2% of the dry weight respectively for the endocarp, covered by a shell, containing oil. Which properties are different from those obtained from the outer husks when people come out and call this part of the product as kernel oil (Nakorn 2005).

Due to the uncertainty in the commercial supply of used frying oil as raw material, it is necessary to turn to agricultural products with more stable yields and continuous production. If there is still land for cultivation in which many other vegetable oils are readily available, such as jatropha, sunflower, castor, coconut, or even rubber seed, the yield is the most reliable must be given to palm oil which is not currently grown only in the south there is still distribution in the central, eastern, northern, and northeastern regions or throughout the country.

Oil can produce two types of oils:

1) Palm oil extracted from palm pulp.
2) Palm Kernel Oil extracted from palm kernels.

One palm fruit contains 9 palm oil while the oil extracted from fresh palm fruit contains beta-carotene, provitamin A, and vitamin E (Vitamin E) in high amounts.

Palm oil contains unsaturated fatty acids and saturated fatty acids in balanced proportions because of the high vitamin E. Therefore, the stability of palm oil is high in unsaturated fatty acids, most are composed of mono-unsaturated oleic acid 40%, while saturated fatty acids are comprised of 44% palmitic acid and 5% stearic acid. The proportion of such ingredients gives palm oil special properties, suitable for use in many types of food processing industries.

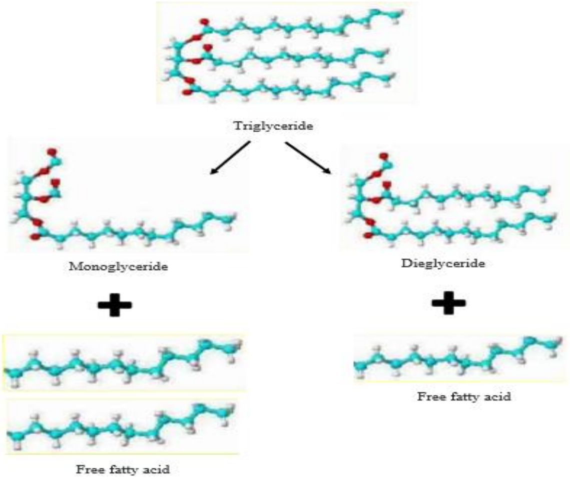


Figure 2.6 Structure of vegetable and animal oil (Kincs, 1985)

Vegetable or animal oils are composed of 1 part glycerol + 3 parts fatty acids called triglycerides. But in all three fatty acids, they react with water to make the fatty acids come off the glycerol one by one. This is called free fatty acid (FFA-Free Fatty acid).

This free fatty acid is like a worm blocking the reaction. If it comes into contact with alkali, it will immediately cause the soap and cause the alkali to catalyze the reaction. There are not enough numbers to catalyze the reaction.

2.4.1 Economic importance of oil palm

Oil palm is a plant with a higher competitive potential than other oil crops. In terms of production and marketing, the world's share of palm oil production to vegetable oil tends to increase. continuously and rapidly, from 11.7 percent during 1976-2000 to 27.5 percent during 2001-2005, and is expected to increase to 31.2% during 2016-2020, with key producing countries Malaysia and Indonesia. According to the Office of Agricultural Economics as of December 2004, there are about 2.2 million rai of oil palm plantation in Thailand, of which 656 thousand rai is in Krabi province, followed by 596 hundred thousand rai in Satun, followed by Surat Thani. 1.01 hundred thousand rai and in other provinces totaling 3.85 hundred thousand rai, it can be seen that the total area of oil palm plantation in 3 provinces, namely Krabi, Surat Thani, and Chumphon, has a total area of 83% of the country's cultivated area, continually expanding and increasing.

According to the Ministry of Energy's goal is to use biodiesel blended with diesel fuel by at least 10% nationwide by 2012, which must be produced at least 8.5 million liters per day, it has to expand the number of oil palm plantations up to 10 million rai to support this production under the supervision of the Department of Agriculture, which is an important approach in response to the country's major renewable energy goals, resulting in the use of raw materials available in the community to produce energy. Self-use can help stimulate the economy and reduce external dependence.

2.4.2 Palm oil extraction process

There are three methods of palm oil extraction in Thailand, namely the Ain-based process, which is the standard method of roasting or blending palm fruit, and the frying process, which yields two major types of palm oil. The pulp in palm kernels is called palm kernel oil and the part obtained from mesocarp is called palm oil a liquid called palm olein, a commonly used oil, and a solid fraction called palm stearin.

2.5 Palm fatty acid distillate (PFAD)

Palm fatty acid distillate is a by-product of pure palm oil distillation in the deodorization process. Deodorization is the removal of odor and flavor substances from the oil. The compounds that have been eliminated are volatile, such as free fatty acids, aldehydes, ketones, and peroxides, which have the following components: free fatty acids about 81.7 percent, Triglycerides about 4.1 percent, diglycerides about 7.6 percent approximately 2.7 percent monoglycerides, and other substances such as hydrocarbons sterols tools properties of PFAD. It will solidify at normal temperature and looks white semi-solid. But if it is brought through heat, it will get molten fatty acid. It looks like a clear yellow liquid. It is commonly used as a raw material for making soap and used as a precursor for the extraction of fatty acids or extraction of vitamin E in the orio chemical industry. After the oil palm bunch is harvested the produce will be transported to the industrial factory where the palm oil is extracted. Which has 2 types of oil extraction processes, standard (separate oil chest) and mixed oil chest. The standard industrial oil extraction plant will have a high production capacity of 30 to 80 tons per hour and oil that has been classified as a grade of quality oil, due to the separation of palm oil types. For factories that extract oil in a mixed oil, the chest will be a factory with relatively low capacity and the extracted oil is an oil that is a mixture of palm oil from the husk and oil from palm kernel. Therefore, we will discuss the methods of oil extraction that are commonly used as a standard.

PFAD is a by-product of a product produced during the refining process of refined palm oil from raw materials, crude palm oil (CPO) (Shuit and Tan 2014), resulting from the refining process of crude palm oil and typically contain 3–5 wt.% free fatty acids (FFA) composition, which need to be reduced to meet refined, bleached and deodorized standards. must be <0.1%. Therefore, PFAD is formed during the crude palm oil refining process. PFAD contains more than 80 wt.% of FFA, triglycerides, diglycerides, monoglycerides. and components that cannot dissolve in water, such as vitamin E. The amount of PFAD produced is about 5%. It can be used as animal feed and as a raw material for soap and oleochemical products. as well as feedstock for biofuel production (Xu, Lee et al. 2020). It is highly potent, low-cost, and is used as a source of fatty acids in the non-food industry. It is used as a clean fuel in machinery and radiators for generating electricity (Lee and Ofori-Boateng 2013). Normally PFAD is semi-solid light brown at room temperature conditions 80% of the main components are free fatty acids, palmitic and oleic fatty acids, and other components in triglycerides (Metre and Nath 2015).

The molar ratio between fatty acids and methanol is 1:1. Since PFAD has an FFA composition of up to 80 %wt (varies from 85% to 100%), the esterification process is suitable for the conversion of PFAD to methyl ester. Before starting production with the esterification process. The first step is to dissolve the PFAD into a liquid usually solid at room temperature, PFAD are generally heated to melt (50-90 °C) to make solid PFAD liquid (Malvade and Satpute 2013, Hosseini, Janaun et al. 2015).

Table 2.3 Properties of PFAD

Properties	Ping and Yousof, 2009	Lokman Ibrahim M., et al., 2015
FFA contant (as palmitic, %)	72.7 – 92.6	86.3 ± 1.75
Iodine value, (l2g /100g)	46.3 – 57.6	-
Saponifiable value (mg KOH/g)	200.3 – 215.4	149.74 ± 4.72
Unsaponification matter (%)	1.0 – 2.5	-
Moisture content (%)	0.03 – 0.24	0.089 ± 0.004
Titre (°C)	46.0 – 48.3	-
Fatty acid composition (wt.%): $C_{14:0}$	0.9 – 1.6	1.9 ± 0.05
Fatty acid composition (wt.%): $C_{16:0}$	43.0 – 49.1	45.7 ± 1.32
Fatty acid composition (wt.%): $C_{18:0}$	4.0 – 4.5	4.3 ± 0.09
Fatty acid composition (wt.%): $C_{18:1}$	34.7 – 37.2	40.2 ± 1.12
Fatty acid composition (wt.%): $C_{18:2}$	8.5 – 9.7	7.9 ± 0.21

PFAD is a raw material that can be used as a low-cost biofuel. It is mainly used as a source of fatty acids for non-industrial applications. It is also used as an environmentally friendly fuel in boilers and power generation engines (Lee and Ofori-Boateng 2013). During the refinery process of CPO, PFAD is typically in the deodorizing stage volatile compounds are removed at this stage. This is considered a by-product of low value (Shuit and Tan 2014 and Abdul Kapor, Maniam et al. 2017).

Table 2.4 Typical fatty acid composition-common oil source (Kincs, 1985)

Fatty acid	Soybean	Cottonseed	Palm	Lard	Tallow	Coconut
Lauric	0.1	0.1	0.1	0.1	0.1	46.5
Myristic	0.1	0.7	1.0	1.4	2.8	19.2
Palmitic	10.2	20.1	42.8	23.6	23.3	9.8
Stearic	3.7	2.6	4.5	14.2	19.4	3.0
Oleic	22.8	19.2	40.5	44.2	42.4	6.9
Linoleic	53.7	55.2	10.1	10.7	2.9	2.2
Linolenic	8.6	0.6	0.2	0,4	0.9	0.0

2.6 Microwave heating

A microwave is a type of high-frequency electromagnetic wave that the eye cannot see it can only be measured using a specific instrument and electromagnetic waves, as well as ultraviolet light and gamma rays but microwaves are not micro in size, instead, they have wavelengths ranging from millimeter to meter scale. The common frequencies of a microwave are between 300 MHz (100 cm) and 300 GHz (0.1 cm) with a maximum wave frequency of approximately 2,450 million cycles/second. They are used for industrial purposes at frequencies in the 915 - 2,450 MHz range. In the electromagnetic spectrum, a microwave is situated between infrared and radio wavelengths, hence it is a considerably large wave as compared to other types of electromagnetic radiation, (Wong, Ng et al. 2019) while the remaining microwave frequencies are reserved for research and other applications. Microwaves are electromagnetic waves whose properties travel in a straight line and move in the air at the speed of light microwave technology is now widely applied in the healing process of materials and substances in a wide variety of businesses and industries such as cooking, chemical synthesis, drying of food, and various work pieces.

The main use of microwaves is to generate heat. which is usually used in household microwave ovens, which will have a frequency of 2.45 GHz. Basically microwaves produced by magnetrons are electromagnetic waves which will consist of electric and electromagnetic fields that are perpendicular and moving in the same direction. The electric field interacts with the dielectric of materials such as polar molecules. This creates an orderly arrangement of the molecules and travels according to the direction of the electromagnetic field and there will be vibration of molecules resulting in friction and become heat energy. The ions also have the function of helping to heat the liquid medium when the electric field is redirected. This results from the propagation of waves in the form of heat. Microwave heating is more efficient compared to conventional heating (Wong, Ng et al. 2019). Microwave heating is a well established method of accelerating, reducing time, and reducing energy to improve chemical reactions. Since it is necessary to transfer energy directly to the substrate and heat transfer from microwave waves is more efficient than conventional heating and the reaction time is much shorter. Therefore, microwave heating is one of the best ways to reduce the reaction time and achieve higher yields in biodiesel production.

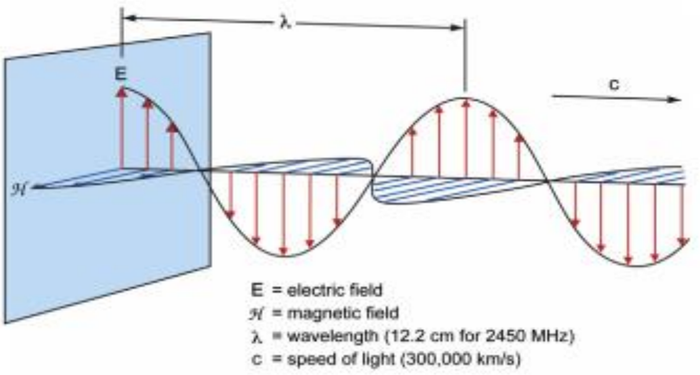


Figure 2.7 Electric (E) and magnetic (H) field components in microwaves. (Falciglia, Roccaro et al. 2018)

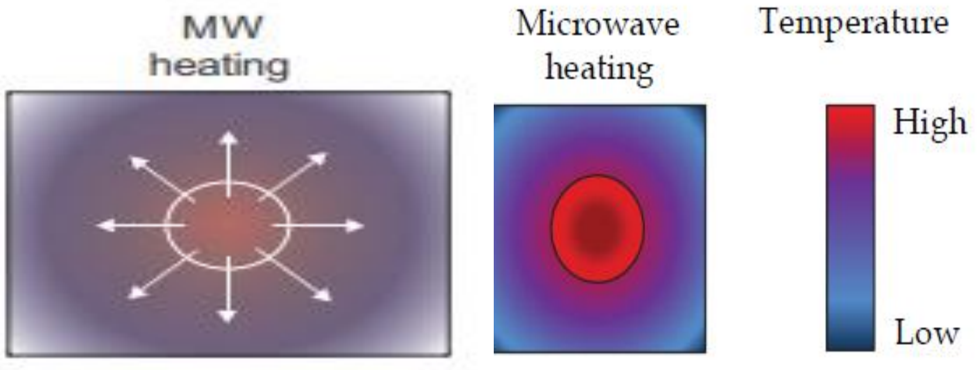


Figure 2.8 The distribution of heat within the substrate when heating in a microwave (Fernandez et al., 2011 and Falciglia, Roccaro et al. 2018)

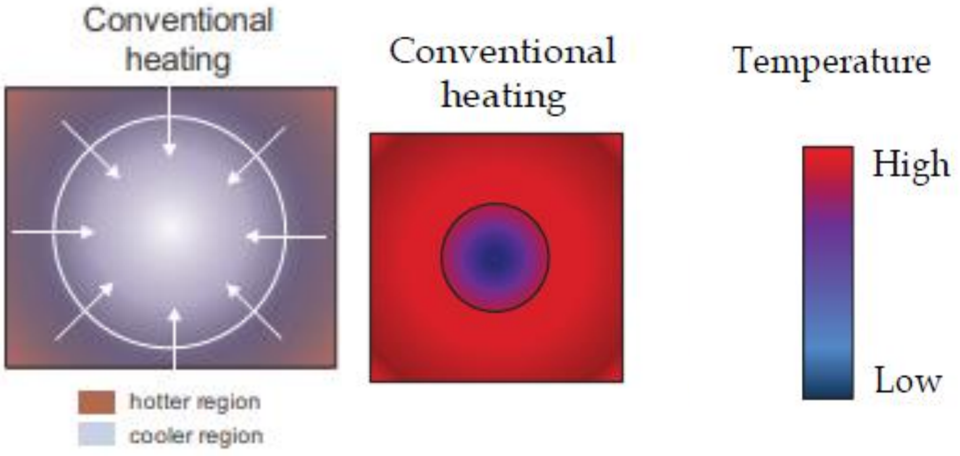


Figure 2.9 Internal heat distribution of material when heating by conventional methods (Fernandez et al., 2011and Falciglia, Roccaro et al. 2018)

The basic working principle of microwave heating is that the molecular structure of many materials can absorb microwaves differently. Microwave waves induce and stimulate substances that can absorb microwaves. Causing the molecules to vibrate and friction until the inside of the material heats up (Majetich and Hicks 1995, Mutyala, Fairbridge et al. 2010).

The process is different from heat transfer. In general, the heat from the source travels through various media in the form of conduction, convection, heat, or radiant heat before reaching the material to be heated, then the heat is transferred to the inside of the material. The vibration of molecules of many materials or substances. It will be a lot. This also depends on the internal bonding force of the particle, the intermolecular bond, as well as the intrinsic resistance of the substance used (Loupy, Perreux et al. 2001). The effects of microwave heating on the reaction were both thermal and non-thermal.

The heat is generated by the action of microwave waves to react with the chemical molecules (Figure 2.10). With conventional heating, the heating rate is inefficient and slow. Caused by energy transfer, convection, and heat. Molecular friction generated by microwave heating generates heat by applying a magnetic field to polar molecules. Therefore, the microwave heating biodiesel reaction can be completed efficiently in a shorter time. and reduced power loss (Athar and Zaidi 2020).

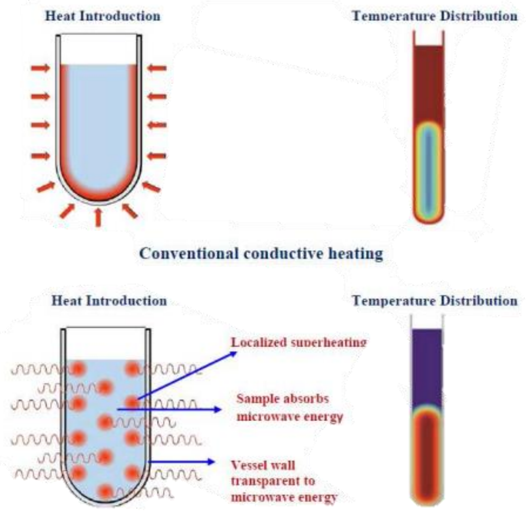


Figure 2.10 Heating mechanism of conventional and microwave heating processes (Athar and Zaidi 2020).

In addition to the energy transfer properties of the microwave material that are different from the conventional heat transfer mentioned above, microwaves also have different properties for traveling through different mediums and materials in 3 forms, both of which 3 of these patterns will affect the application of microwave waves.

1) Microwave transmission can penetrate non-conductive materials such as glass, paper wood, ceramics, and plastics. Because the container does not mix metal. It is a material that works well with a microwave oven and also allows microwave waves to penetrate easily.

2) Reflection when microwave waves hit a metallic material or a mixture of metals, microwave waves cannot penetrate the material, causing total reflection. Therefore,the material used as the reactor body or the substance to be applied in the microwave process should not be a metallic material or a metal-containing material because the metallic material will cause the microwave to reflect. Causing the magnetron to deteriorate quickly and the service life of the microwave oven is shortened as well as the energy consumption as well.

3) Adsorption,some materials can absorb microwave waves, and when the molecule of that material absorb microwave waves will heat the substance quickly and when that molecule absorbs a microwave wave, it instantly becomes heat and does not accumulate in that substance the properties mentioned above of the microwaves are one of the most important factors when choosing a material or substances that will be used in the microwave heating process. Including as a precaution in reactor design and various equipment parts to be used with the microwave in order not to affect the work system, no energy consumption, and for maximum efficiency as well as considering the safety when using.

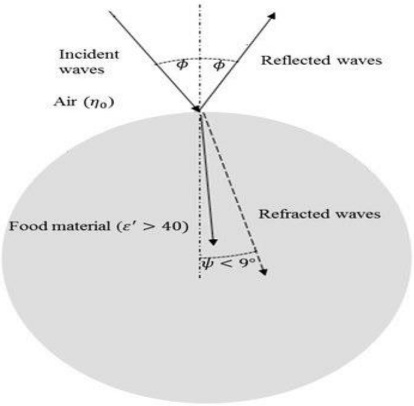


Figure 2.11 Microwave reflection in food material (Tang 2015)

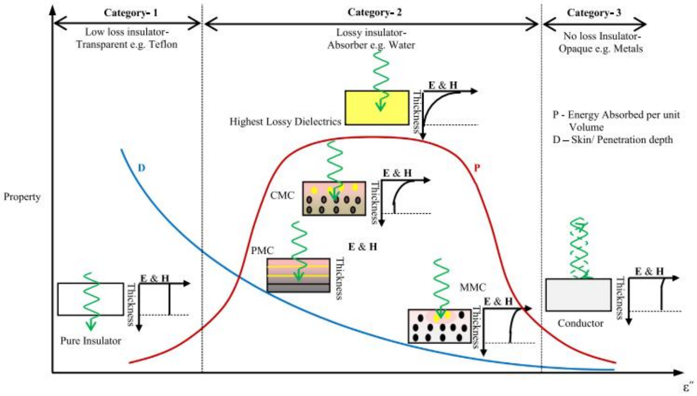


Figure 2.12 Microwave interaction with materials (Mishra and Sharma 2016)

From the above working principle, microwave heating takes a shorter time to generate and it loses less heat than traditional heating processes in that heat is wasted with various forms of heat transfer, thus saving time, saving energy, and helping reduce costs production is also a technique that improves and improves product quality (Domínguez, Menéndez et al. 2007).

In general, the microwave heating process requires three basic components: a microwave source or generator, a microwave waveguide, and applicators that contain raw materials or samples with details as follows.

A microwave source or generator consists of a direct current source and the magnetron, which acts as a device to generate microwave waves, using a method of converting high-voltage direct current energy to microwave energy. In general, the magnetron is classified into two types: the rhythmic type, which is mainly used in radar applicators and the other continuous working type. Which is mainly applied to thermal processes such as home microwave ovens and industrial microwave heating. When the magnetron generates a microwave wave, it travels the applicators through a wave tube. Usually, rectangular tubes are made of brass or aluminum. The size inside the wave tube must be suitable for the properties of the microwave wave to travel to the applicator it is mostly made of metal materials. It depends on the type of cavity and wave pipes one of the major problems with a cavity is the inconsistency of the microwave wave that the load received which affects heat dissipation within the load. Therefore, to make the loads inside the cavity regularly to microwave waves. It has therefore been improved to have a rotation of the load, which may use a rotating tray in the case of a microwave oven. Also, a stirring blade is installed to act as a stirring of the energy field to make the load more thoroughly microwaved.

Table 2.5 Process techniques for biodiesel production (Athar and Zaidi 2020)

Techniques	Principle	Advantages	Disadvantages
Microwave heating	Heat is caused by the friction of molecules caused by a disorderly arrangement when there is no electric name outside but when an electric field is applied to the molecules, they form an orderly arrangement in the direction of the electromagnetic wave and turned into heat energy.	• Consistent and precise heat • Less surface overheating • Waves penetrate directly into the product • Reactions occur efficiently and in a short reaction time • Reduce separation and purification time • Does not negatively affect the environment. • High thermal efficiency • High heat rate	• Microwave penetration depth is only a few centimeters • Requires mixing outside the reactor • Safety in the pressure section inside the reactor

2.6.1 Microwave magnetic field heating mechanism

The heat generated by the microwave magnetic field is different from heat generated by electric field Dielectric, heat, current loss, and magnetic resonance loss are important and the main mechanisms for magnetic microwave heating. Vortex currents occur when conductors are exposed to a changing magnetic field due to various sources and field conductors. Eddy current loss is the main mechanism of microwave heating of materials. In magnetic materials such as iron, nickel and other metals, hysteresis is lost. The heating principle occurs when the magnetic material is subjected to an electromagnetic field. The magnetic poles then vibrate and change direction every turn, where the rapid reversal of the magnetic field causes friction and heat within the material. This oscillation mechanism is called loss hysteresis. causing the hysteresis loop mechanism the hysteresis loss affects the heating of magnetic materials in an electromagnetic field.

2.6.2 The advantages of microwave heating

Conventional heating will occur outside of the material and microwave heating will generate volumetric heat and general heat generation characteristics Occurs when heat is transferred from the outer surface of the material. It was observed that the surface of the material burned and was unable to distribute heat throughout the material. But microwave heating is generated from the inside of the material and is distributed to the surface of the material (Popescu, Misawa et al. 2008). The heat generated by microwaves is more efficient and economical than conventional heating. This is because the material can be heated directly without the need for heat from the outside (Salema and Ani 2011, Abubakar, Salema et al. 2013). Also, microwave provides heating that was consistent and fast (Salema and Ani 2011, Undri, Abou-Zaid et al. 2015, Lee, Lee et al. 2017). Microwaves were commonly used in various fields more efficiently compared to conventional heating. Due to its advantages in many areas such as high rate of heating, non-contact heat, good heat transfer, the heat generated within the material, easy to control (quick start and stop), and is automated. Table 2.6 shows the difference between microwave and conventional heating.

Table 2.6 The difference between microwave and conventional heating (Yin 2012)

Microwave heating	**Conventional heating**
Energy conversion	Energy transfer
Volumetric heating: all materials were heated simultaneously at the molecular level.	Superficial heating: all materials were heated via convection or conduction.
Rapid and efficient heat generation	Slow heat generation, is inefficient, depending on the thermal conductivity properties of the material.

Selective: heat occurs quickly for dielectric materials.	Non-selective
Hotspot: The effect of the electromagnetic field or dielectric properties causes the temperature inside the material to be higher then the measured temperature in the bulk	No hot spot
Precise and controlled heating: power ON or OFF, power input will start and stop immediately respectively	Less controllable

2.6.3 Temperature control system

A Control system means a device or tool used to control the work according to the setting. There were several methods of control such as ON-OFF temperature control and PID control. ON-OFF control was generally the most common type of control used in industry, as the choice of discrete actuators such as relays or electromagnetic coils was easier and cheaper to use continuous type actuators. ON-OFF controllers were an integral part of industrial and laboratory equipment (Ryniecki, Wawrzyniak et al. 2015). Which here presents an on-off temperature control. It was a system that works in 2 states, open and closed. Therefore, the control output signal had only 2 states, ON (0) and OFF (1). This operation was defined by the process error value according to the equation.

This research uses the thermal couple type-K to detect an analog signal in the form of a voltage signal, performed by an ON-OFF temperature control system. This SSR was an electrical on-off switch that was supplied to a microwave power supply. Moreover, electrical signals were sent to the temperature control device directly. Then, the temperature value will be displayed as a digital number on its screen and data will be recorded by connecting the personal computer (PC) via RS485.

2.7 Engine test

The internal combustion engine commonly used in automobiles can be divided into two main types: A spark ignition engine (SI engine) or popularly known as the gasoline engine and a compression ignition engine, CI engine, also known as the diesel engine this test is to test the diesel engine to determine the performance related to the internal combustion engine.

2.7.1 Engine performance

Internal combustion engines, especially reciprocating engines, have many variables involved some things can be easily measured until variables that require special tools to measure in this section, the variables related to diesel engine performance are discussed. It is limited only to those that can be determined with existing testing tools which consists of the following variable.

Table 2.7 Variables used in engine calculations

Symbol	**Variable**	**Unit**
N	Engine speed	rpm
W	Brake torque	lbf.ft
P	Brake power	kW
BHP	Brake horse power	HP
BSFC	Brake-specific fuel consumption	kg/kW-hr
BTE	Brake thermal efficiency	%
$v^{\cdot}$	Specific input fuel by volume	m^3/hr
ρ	Fuel density	kg/m^3
$\dot{m}$	Specific input fuel by mass	kg/hr
LHV	Low heating value	kJ/kg

The definitions and relationships of variables are as follows.

1) Brake power (P)

Braking power is the engine power obtained by measuring the work done from the engine's crankshaft at the engine speed by using a dynamometer to measure the resulting torque the braking power can be calculated as follows:

$$P \quad = \quad 0.746 \text{ BHP}$$

P (kW) = Brake power

BHP (HP) = Brake horse power

2) Brake-specific fuel consumption (BSFC)

The specific fuel consumption is mass fuel consumption per unit of the power produced by an engine over some time by testing the engine, the specific fuel consumption was measured as the mass flow rate. The large engine will have a lot of fuel consumption. Therefore, in comparison, the fuel consumption of engines of different sizes in this the form of brake-specific fuel consumption (BSFC), which is the mass flow of fuel per unit of brake power produced as shown in this equation.

$$\text{BSFC} = \frac{\dot{m}}{\text{P}}$$

P (kW) = Brake power

BSFC (kg/kW-hr) = Brake-specific fuel consumption

$\dot{m}$ (kg/hr) = Specific input fuel by mass

3) Brake thermal efficiency (BTE)

Thermal efficiency It is a value that indicates how efficiently the engine can convert the heat received from the fuel to how much work thermal efficiency can be defined in two types: indicative thermal efficiency and brake thermal efficiency. The braking thermal efficiency is approximately 30 percent very large slow-rotating diesel engines may be greater than 50 percent, as shown in this equation.

$$\text{BTE} = \frac{3{,}600 * 100}{\text{BSFC} * \text{LHV}}$$

BTE (%) = Brake thermal efficiency

BSFC (kg/kW-hr) = Brake-specific fuel consumption

LHV (KJ/kg) = Low heating value

2.7.2 Diesel engine test

In the internal combustion engine, in general, there will be several testing methods but the most popular type there are 2 type is full load testing. In the case of diesel engines, this type of test is to increase the throttle. Observe the exhaust gas produced by the engine if the exhaust gas starts to turn gray. This shows that the amount of fuel that enters the cylinder is enough and begins to burn out. Which is considered the amount of water the maximum fuel already supplied can be fully utilized. The load given to the engine is then adjusted to determine the relationship of the engine rpm to the load each load adjustment requires a new throttle adjustment, observing the exhaust gas every time. Therefore, such a test is quite difficult for diesel engines.

Another popular test for diesel engines is the constant engine speed test, which adjusts the engine's throttle according to the load. Maintaining a constant engine speed (for constant speed control, it may be difficult in practice. Therefore, the discrepancy of the engine speed from 5 to 10%) is preferred. This test aims to find the relationship between the average braking effect (BMEP) and the relative braking fuel consumption (BSFC) and the brake thermal efficiency of the engine at the rated speed is the main.

2.8 Cost analysis

Cost benefit analysis is the process of calculating income or expenses that may arise Then subtract all related costs or related products (Pair 2018).

2.8.1 Production cost

The cost of production is the cost of producing a certain product the cost of production or manufacturing cost consists of 3 parts: material cost, labor cost, and factory cost. Manufacturing overhead by each part of the production cost or manufacturing cost has the following meanings:

1) Material cost is the cost of production that comes from the cost of raw materials of that product, which varies for each type of product, for example, the production of green tea will have costs from water and tea leaves, etc.

2) Labor cost is the expense incurred from processing raw materials to finished goods factory expenses.

3) Manufacturing overhead, sometimes called overhead, is any other expense that does not vary with the number of productions. Most factory overhead costs are usually fixed costs (Pair 2018).

CHAPTER 3

METHODOLOGY

3.1 Materials

In this experiment, PFAD, which was obtained from crude palm oil (CPO) refining in the area of Surat Thani province, Thailand was supported by New Biodiesel Co., Ltd. PFAD was used as the main raw material for biodiesel production.

Methanol is used as alcohol, purchased from Modern Chemical Co., Ltd., commercial-grade purity of 99.85 wt.%.

Sulfuric acid from Modern Chemical Co., Ltd. analytical reagent (AR)-grade purities of 98 wt.% was used as a catalyst for the esterification process with 2% wt./wt.

3.2 Equipments

Equipments were used as follows:

1) Microwave reactor; dimensions x×y×z: 312×352×360 mm.
2) Two magnetrons operating at a frequency of 2.45 GHz, and power 1,000 watts.
3) Thermocouple type-K size 1*150 mm.
4) Solid-state relay
5) Temperature controller; SHIMAX model MAC3D-MSF-EN-NRN
6) Software Shimax
7) USB RS485 serial port converter
8) Datalogger
9) Watt-hour meter
10) DURAN glass bottle of 2,000 ml.
11) Hot plate
12) Magnetic bar
13) Separatory funnel
14) Rotary evaporator
15) Weighing machine
16) Funnel
17) Oil sample bottle

18) Thermometer
19) Gas stove
20) Glassware
21) Diesel engine model KUBOTA RT100 DI Plus
22) Personal computer

3.3 Schematic diagram of microwave-assisted biodiesel.

This research studied the conditions for biodiesel production from the palm fatty acid distillation (PFAD) with 3 variables, namely by PFAD to methanol ratio, reaction temperature, and reaction time. The engine test was performed for the properties testing of biodiesel according to the announcement of the Department of Energy Business. The study plan is detailed in Figure 3.1

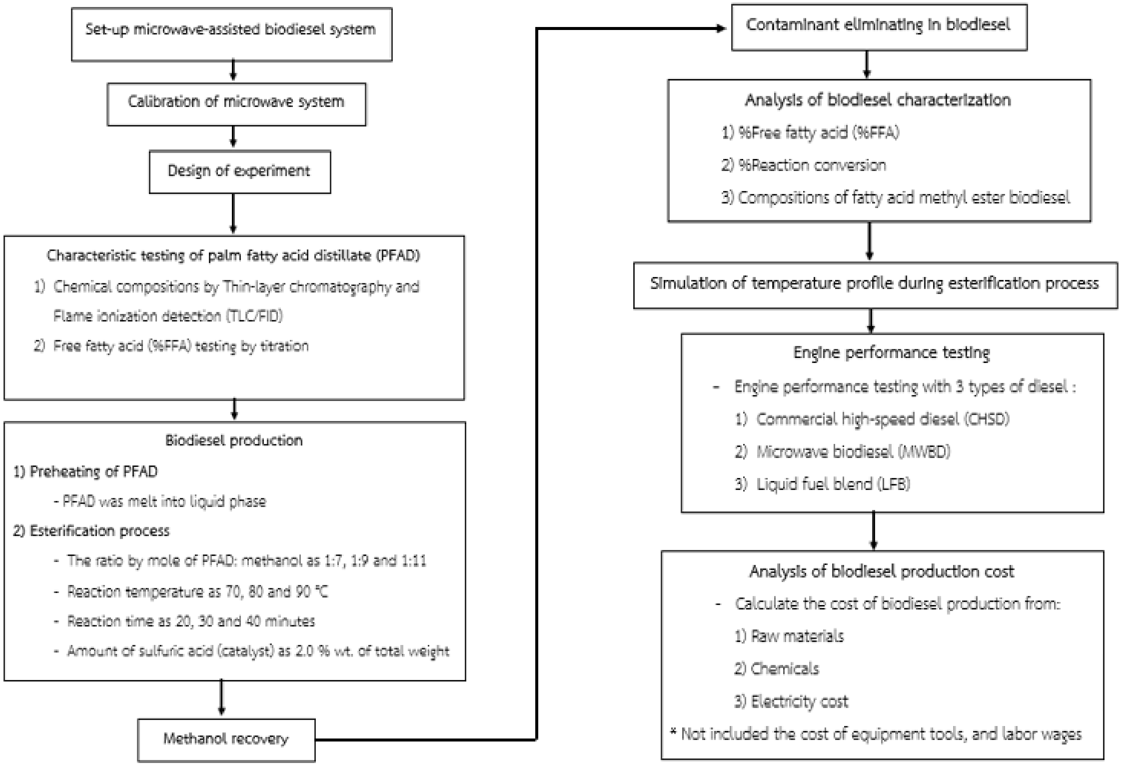
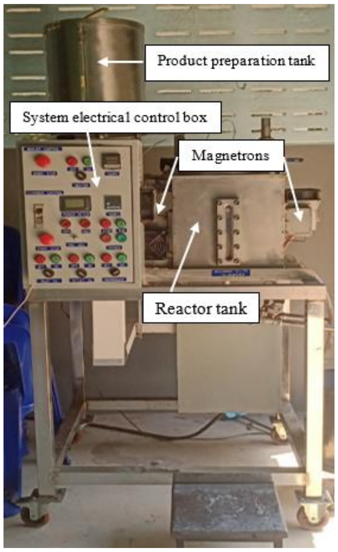


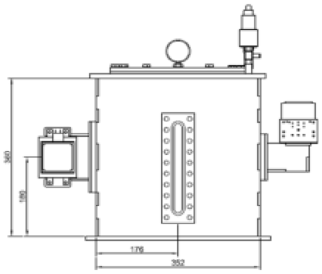
Figure 3.1 Schematic diagram of microwave-assisted biodiesel production.

3.4 Methodology

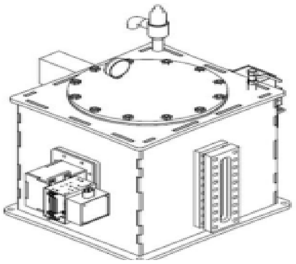
Part 1: Set-up microwave-assisted biodiesel system

The batch microwave-assisted biodiesel system consisted of two magnetrons placed on rectangular waveguides, which were located on opposite sides of the cavity asymmetrically as shown in Figure 3.2 The waveguides were operated in transverse electric field (TE10) mode. These magnetrons operated at 2.45 GHz frequency and a maximum power of 1,000 watts. They were connected to a microwave (MW) switching mode power supply (Enbiens: YB-MP1000). The temperature was controlled by the Shimax™ Co.,Ltd model MAC3D-MSF-EN-NRN, which was connected to a type-K thermocouple. A Duran 2000ml glass bottle was used as the reactor and was placed inside the MW cavity. The cavity had the dimensions312×352×360 mm and a ground cable was installed using copper rods buried in the ground and connected to the microwave to reduce interference when the microwave was opened.





b) Reactor front view



a) Microwave-assisted biodiesel system.

c) Reactor side view

Figure 3.2 Microwave-assisted biodiesel system.

A temperature control was installed on microwave-assisted biodiesel. The type-K thermocouple 1X150 mm can provide an analog signal from the reactor to the temperature controller (model SHMIAX, MAC3D-MSF-EN-NRN), solid-state relays (SSR) and acts as a switch to turn on-off the power on the supply from the microwave, with USB RS485 acts to control the temperature by sending data to a personal computer. The method of operation was set the desired temperature in the experiment set the maximum and minimum temperature (±0.5), and real-time temperature display and all data can be collected through Shimax software. Figure 3.3 shows the temperature controller and USB RS485 port.

(a) (b)

Figure 3.3 (a) Temperature controller, and (b) USB RS485

Part 2: Calibration of microwave system

After the design and building of microwave-assisted biodiesel (MAB). Therefore, a preliminary test of the microwave system was performed using tap water as a calibrator. The microwave system was performed as shown in Figure 3.4

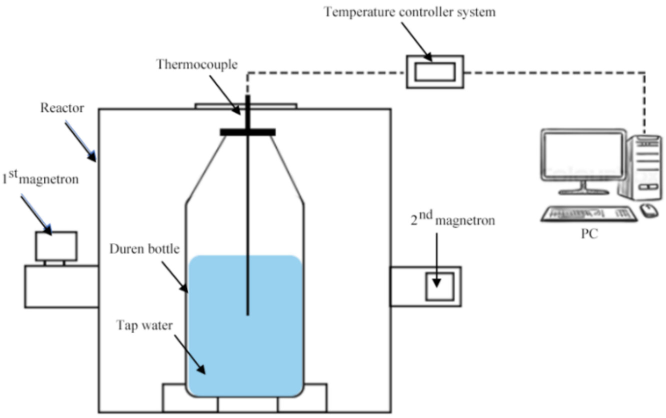


Figure 3.4 Calibration with tap water of microwave system for biodiesel production.

The experiment was carried out by placing tap water in a 2,000 ml Duran bottle and controlling the tap water temperature to 80 ± 0.5 °C for 2 minutes to test the temperature control of the microwave system.

Part 3: Design of experiment

The Box–Behnken experimental design was used to optimize the %FFA conversion with three factors and three levels, as shown in Table 3.1. such as the molar ratio of PFAD to methanol (1:7, 1:9, and 1:11 mol), reaction temperature (70, 80, and 90 °C), and reaction time (20, 30 and 40 minutes) where is defined amount of sulfuric acid catalysts is 2.0 %wt. The design of experiments in this study is shown in Table 3.1. These levels were designed after reviewing the results of (Noureddin, 2014). The review showed that a high proportion of methanol was required, depending on the kind of feedstock oil; moreover, the reaction temperature was higher than that of methanol reflux in a continuous system because the microwave-assisted conversion was performed in a closed batch system for a specified reaction time.

Normally, PFAD is a white-yellow soft wax at room temperature and takes the form of a clear liquid with light brown color at around 50 °C, so before using PFAD, it was heated to 50 °C and mixed in the desired molar ratio with methanol (MeOH), and commercial sulfuric acid (H_2SO_4 at 98% concentration) was added to 2 wt% of the liquid mixture as an acid catalyst, so that the total volume of the liquid mixture was 1,800 ml in every experimental run. The liquid mixture was then loaded into the Duran batch reactor, which was placed inside the microwave cavity to produce MWBD by esterification. The optimal operating point giving the maximum %FFA conversion at the minimum cost (USD) would be selected (by optimizing with the fitted models) to produce liquid MWBD and test it in a single-cylinder diesel engine.

Table 3.1 Factors and their levels in the experimental design by Box–Behnken.

Variables	**Acronym**	**Level**		
		-1	**0**	**1**
The mole ratio of PFAD to methanol	R	1:7	1:9	1:11
Reaction temperature (°**C**)	T	70	80	90
Reaction time (minutes)	t	20	30	40

Part 4: Characteristic testing of palm fatty acid distillate (PFAD)

Method 1: Determination of the chemical composition of PFAD by thin layer chromatography and flame ionization (TLC/FID) detection at the Faculty of Engineering. mechanical engineering sector Prince of Songkla University Hat Yai Campus.

Method 2: Determination of Free fatty acid (%FFA) constituents by titration method and substitute the values obtained in the equation to find the %FFA value as the following equation.

Part 5: Biodiesel production with microwave heating of PFAD

5.1) Preparation of materials for the biodiesel production microwave-assisted biodiesel.

1) PFAD preparation

In biodiesel production with microwave heating process, PFAD, which was obtained from crude palm oil (CPO) by New Biodiesel Co., Ltd., which is located in Tha-Chang district, Surat Thani province, Thailand. PFAD was used as the main raw material for biodiesel production. Before biodiesel production, this raw material must dissolve to become liquid. The PFAD was analyzed by Thin-layer chromatography and Flame ionization detection (TLC/FID; IATROSCAN MK-6s, SES Germany) to find the composition of PFAD.

2) Alcohol preparation

The most common alcohol used in biodiesel production is methanol, although other alcohol such as ethanol, isopropanol, and butyl can also be used. Methanol used as alcohol, purchased from Modern Chemical Co., Ltd., commercial-grade purity 99.85 wt.%. The mole ratio of PFAD to methanol was studied at 3 levels such as 1:7, 1:9, and 1:11.

3) Sulfuric acid preparation

Sulfuric acid from Modern Chemical Co., Ltd., analytical reagent (AR)-grade purities of 98 wt.% were used as a catalyst for the esterification process with 2% wt./wt. The catalysts that are commonly used for biodiesel production of free fatty acid are sulfuric acid and phosphoric acid and the catalyst is mixed with methanol and raw material with a high content of free fatty acids and free fatty acids will convert to biodiesel. This is because the raw material and mixture between the catalyst and methanol are in opposite move directions.

The purpose of this experiment was to study the optimum conditions for biodiesel production by microwave heating under three conditions, namely PFAD to methanol ratio by molar, reaction temperature, and reaction time that affect the yield and properties of biodiesel from PFAD

The controlled variable in this part experiment is as follows:

1) Microwave-assisted biodiesel with 1,270 watts of power
2) Amount of sulfuric acid as a catalyst is 2.0 wt.%

To produce biodiesel, the first step is to dissolve PFAD into liquid. Then pour the heated PFAD into a DURAN bottle followed by methanol and sulfuric acid according to the experimental design and stir the ingredients together and close the lid of the bottle. Then put the Duran flask with the mixture of the ingredient into the reactor, and start the experiment.

Normally, palm fatty acid distillate (PFAD) is a white-yellow soft wax in a room temperature and takes the form of a clear liquid with a light brown color of around 50 ℃. Before using PFAD, it was heated to 50 ℃ and mixed in desired molar ratio with methanol (MeOH), and the commercial sulfuric acid (H_2SO_4 at 98% concentration) was added to 2 wt.% of the liquid mixture as an acid catalyst and the total volume of the liquid mixture was 1,800 ml in every experimental run according to the ratio of the experimental design. After that, the liquid mixture was loaded into the DURAN reactor, which was placed inside the microwave cavity to produce microwave-assisted biodiesel (MWBD) by esterification reaction. The optimal operating point giving the maximum %conversion at the minimum cost (USD) would be selected to produce liquid MWBD and to put it to the test in a single-cylinder diesel engine.

Before starting the test engine performance, the microwave-assisted biodiesel (MWBD) was stirred and heated to evaporate moisture, at 110 ℃ for 30 min stirring with a type of agitator 6-blade disk turbine at a speed of 250-300 rpm and it was characterized for its biodiesel properties by the Office of Scientific Instrument and Testing, Prince of Songkla University, Hat-Yai Campus, Songkla, Thailand. Then, three liquid fuels were prepared: a pure MWBD, a commercial high-speed diesel (CHSD), a 50:50 blend of MWBD and CHAD named a liquid fuel blend (LFB), and a pure CHSD. The CHSD was bought from the Shell fuel station opposite the Prince of Songkla University Hat-Yai Campus.

Part 6: Methanol recovery process

The objective of this experiment was to recovery the methanol left from biodiesel production as shown in Figure 3.5.

The control variables in this section were tested as follows:

1) Rotation speed range as 60 rpm

2) Total volume of the liquid sample as 500 ml

3) Reaction temperature as 60 ℃

The independent variable in this experiment was that for each of the three PFAD to methanol ratios, 1:7, 1:9, and 1:11 moles had unequal volumes of alcohol content as a result, the recovery of methanol in each experiment was not equal in volume.

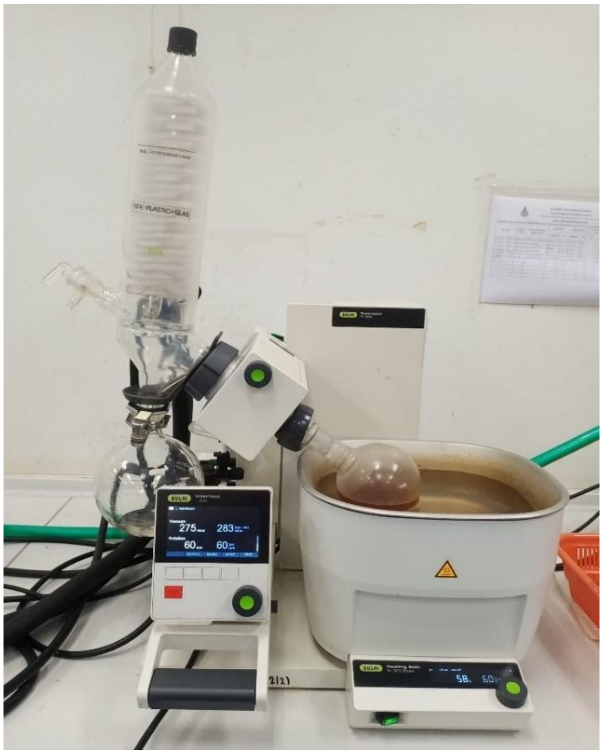


Figure 3.5 Methanol recovery process with a rotary evaporator

Part 7: Contaminant eliminating in biodiesel

The resulting biodiesel has two layers, the top layer is non-reactive excess methanol and the bottom layer is biodiesel. We used the surplus methanol top layer to recover methanol for recycling and the bottom layer, the biodiesel layer. The contaminants are washed from the oil by running warm water through the separator funnel. When the wash is finished, it will be reheated with water at a temperature of 110 **°C** for 30 minutes.

Part 8: Analysis of biodiesel characterization

3.4.1 Preparation of solution for titration

NaOH 0.1 N by weighing 4.2 g of sodium hydroxide was prepared by dissolving in distilled water and adjusted the volume to 1 liter, then stored this solution in a glass flask. And phenolphthalein 1% was prepared by weighing 1 g of phenolphthalein and added 50 ml of 95% purity ethanol by adjusted the volume to 100 ml of distilled water and used ethanol as a solvent.

In every experiment We always titrate the %FFA of the product to find out how much PFAD %FFA decreases before and after the trial. By using the equation %FFA, then calculate to the conversion equation how much of our product converted to fatty acid methyl ester.

$$\%\mathrm{FFA} = \frac{25.6 \text{ x NaOH concentration x NaOH(ml)}}{\text{sample weight (g)}}$$

$$\mathrm{Conversion}(\%) = \frac{\%\text{FFA before reaction} - \%\text{FFA after a reaction}}{\%\text{FFA before reaction}} \text{ x } 100$$

Part 9: Simulation of the liquid mixture temperature profile

Multiphysics simulations were run to assess the period that the temperature steeply increases in the liquid mixture under microwave heating or called the temperature transient period the temperature transient in the liquid mixture under microwave heating, by using the COMSOL, Inc. (Burlington, MA 01803 USA) Multiphysics software package with the assumption that the air surrounding the reaction medium was constant; the liquid mixture in the transient period (60 s) consisted of PFAD and methanol only; and it remained a liquid during the esterification process. The sulfuric acid catalyst was omitted from this simulation, and the model ignored the chemical conversion reactions. Finally, the liquid mixture was in the laminar flow regime and was considered a homogenous single phase solution. The time profile of the temperature in the liquid mixture was obtained by using a type-K thermocouple placed in the middle of the reactor, as shown in Figure. 3.6. The same location was probed in the model simulations for comparisons.

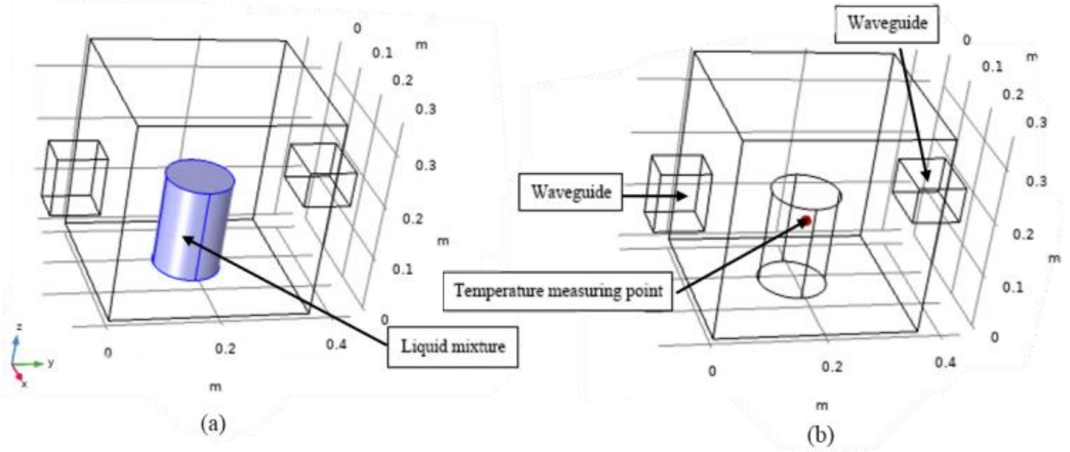


Figure 3.6 (a) Microwave-assisted biodiesel conversion model, and (b) temperature measuring point

The governing equations of the current model consist of Maxwell's equations for electric field distribution, coupled with energy conservation of heat transfer in liquid mixture, and Navier–Stokes equations for mass and momentum conservation of the liquid assumed to have laminar flow conditions, as shown in equation (3.1)–(3.4):

$$\nabla x\, \mu_r^{-1}\left(\nabla x\vec{E}\right) - k_0^2\left[\varepsilon_r - \frac{j\sigma}{\omega\epsilon_0}\right]\vec{E} = \tag{3.1}$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u}\cdot\nabla T - \nabla\cdot(k\nabla T) = \omega\varepsilon_r\varepsilon_r''|E|^2 \tag{3.2}$$

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\vec{u}) = 0 \tag{3.3}$$

$$\rho\frac{\partial\vec{u}}{\partial t} + \rho\vec{u}\cdot\nabla\vec{u} = -\nabla p + \left[\mu(\nabla\vec{u} + (\nabla\vec{u})^T) - \frac{2}{3}\left(\mu(\nabla\cdot\vec{u})\right)\right] - \rho\vec{g} \tag{3.4}$$

Here, $\mu_r$is the relative permeability (Hm^{-1}), j is the imaginary unit, σ is the conductivity (S), ω is the angular frequency (rads^{-1}), ε r is the relative permittivity, ε_0 is the permittivity of free space (Fm^{-1}), ρ is the fluid density (kgm^{-3}), μ is the molecular viscosity coefficient, and $\vec{g}$ is the gravitational acceleration. The liquid mixture properties, which depend on the molar fraction ($x_i = c_i/c_{tot}$; concentration of species i, and total concentration) of each component, were calculated using the molar fractions as weights. The relative complex permittivity, the dynamic viscosity, thermal conductivity, specific heat capacity, and density of liquid mixture for a species i (PFAD and methanol) were therefore calculated as molar-weighted averages, as expressed in equation (3.5)–(3.10). The initial parameters and properties needed in this model are listed in Table 3.2

$$\varepsilon = \varepsilon_0 \sum_{i=1}^{2}\left(x_1\varepsilon_{r,i}\right) \tag{3.5}$$

$$\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'' \tag{3.6}$$

$$\mu = \sum_i x_i\mu_i \tag{3.7}$$

$$k = \sum_i x_i k_i \tag{3.8}$$

$$C_p = \sum_i x_i c_{pi} \tag{3.9}$$

$$\rho = \sum_i x_i\rho_i \tag{3.10}$$

Table 3.2 Summary of initial conditions and parameters applied in the model.

Parameter	Unit	PFAD	Methanol	Liquid mixture ratio		
				1:7	1:9	1:11
Complex relative permittivity (ε_r^*)	-	2.78–0.17j	26.39–10j	23.15–8.66j	23.76–8.92j	24.17–9.08j
Dynamic viscosity (μ)	mPa s	12.75	0.34	0.002	0.002	0.001
Thermal conductivity (k)	W $m^{-1}K^{-1}$	0.17	0.200.19	0.19	0.19	0.20
Specific heat capacity (c_p)	$Jkg^{-1}K^{-1}$	2183	2520	2448	2459	2467
Density (ρ)	kgm^{-3}	885.6	792	794	793	792

Part 10: Engine performance testing

The objective of this experiment was to test biodiesel produced from the best condition for tested engine performance compared to pure microwave biodiesel (MWBD), a commercial high-speed diesel (CHSD), and a liquid fuel blend (LFB) to compare engine performance.

The control variables in this section were tested as follows:

1) Engine speed 2,200 $\pm$ 10 rpm

2) Braking power at 3.9, 7.8, 11.7, and 15.5 $\pm$ 0.5 lbf. ft

3) Fuel volume of 50 $\pm$ 0.5 ml

3.4.2 Analysis of material properties in the biodiesel properties test.

3.4.2.1 A single-cylinder diesel engine test

Before starting the test, the MWBD was stirred and heated to evaporate moisture, at 110 °C for 30min, and it was characterized for its biodiesel properties by the Office of Scientific Instrument and Testing, Prince of Songkla University, Hat-Yai Campus, Songkhla, Thailand. The results are shown in Tables 4.5 and 4.6. The three types of diesel were tested for engine performance testing such as 1) Commercial high-speed diesel (CHSD) 2) Microwave biodiesel (MWBD) and 3) Liquid fuel blend (LFB). The CHSD was purchased from the Bangchak fuel station in Prince of Songkla University Hat-Yai Campus. Since 2015, the Thai government has required CHSD to contain at least 6-7 vol% FAME for promoting energy security and national economy. However, its real composition was not analyzed in this study. The single-cylinder diesel engine Kubota model RT100 DI Plus as shown in the Figure 3.7-3.8 with specifications shown in Table 3.3 was tested on a 12hp Plint & Partner dynamometer, with setup schematically shown in Figure 3.9 The engine was tested at a constant 2200rpm speed (ranging within ±10 rpm) with loads of 1.28, 2.56, 3.86, and 5.09kW±0.5%, and with three replications per load. The actual load ranges tested were the same in terms of computed brake mean effective pressure for a speed of 2200rpm±0.6%. The force delivered on dynamometer with a fixed inside arm length of 1.05ft for the engine test was therefore used to calculate the brake torque and the corresponding brake power was measured using a spring balance, Salter (3.90–19.50±0.05lbf). The volumetric flow rate of fuel was measured using a scaling tube (50.0±0.5mL) coupled with a digital stopwatch, which had a resolution of 0.01s, in the range 88.70–521.97s±0.5%; moreover, the engine speed was measured using an increment encoder model PR-01N-S (resolution 0.1rpm), and a type-K thermocouple (resolution 0.01 °C) was connected to the PC-based data logger, model AI210. It measured the fuel temperature (30.97–37.47 °C) and exhaust gas temperature (EGT: 140.74–465.44 °C±0.5%) and the accuracy of the measured quantities and the uncertainties of calculations are summarized in Table 3.4 The engine test system schematic is shown in Figure 3.9

Table 3.3 Test engine specifications (Eiadtrong, Maliwan et al. 2021)

	Brand Kubota model RT100 DI Plus
Engine type	4 provinces, ignited by compression
Compression ratio	18:1
Number of cylinders - cylinder arrangement	1- horizontal
Width/stroke/volume of the cylinder	88 mm / 90mm / 547 cm^3
Maximum power	7.4 kW – 2,400 rpm
Maximum torque	3.4 kg-m – 1,600 rpm
Fuel injection	Dl-mechanically controlled
Cooling	Water-cooled

Table 3.4 Measurement accuracies and uncertainties of the calculated results (Eiadtrong, Maliwan et al. 2021)

Measure quantity	Accuracy	Calculated quantity	Uncertainty (%)		
			1200rpm	1700rpm	2200rpm
Force on dynamometer set	±0.05 lbf (±0.22N)	Fuel volume and mass flow rates	±1.1	±1.1	±1.1
Engine torque	±0.05 lbfft (±0.07Nm)	Brake power	±0.8	±0.6	±0.5
Engine speed	±10rpm	Brake mean effective pressure (BMEP)	±1.2	±0.8	±0.6
Time for fuel flow rate	±0.5%	Brake specific fuel consumption (BSFC)	±1.4	±1.3	±1.2
Exhaust gas temperature (EGT)	±0.5%	Brake thermal efficiency (BTE)	±1.4	±1.3	±1.2

BMEP, brake mean effective pressure; BSFC, brake specific fuel consumption; BTE, brake thermal efficiency; EGT, Exhaust gas temperature.

Table 3.5 Comparison of fatty acid methyl ester biodiesel standards against diesel standards for agricultural and high-speed diesel engines (Eiadtrong, Maliwan et al. 2021)

Fuel properties	**Test method**	**TS**	
		AED	**HSD**
Density at 15 ℃	ASTM D1298	860-900	810-870
Kinematic viscosity at 40 ℃	ASTM D445	1.9-8.0	1.8-4.1
Cetane number	ASTM D613	≥47	≥50
Higher heating value (kJ/kg)	ASDT D240	n.a.	n.a.
Flashpoint (℃)	ASTM D93	≥120	≥52
Cloud point (℃)	ASTM D2500	n.a.	n.a.
Pour point (℃)	ASTM D97	n.a.	≤10
Carbon Residue (%wt.)	ASTM D482 / D4530	n.a.	≤0.05
Sulphated ash (%wt.)	ASTM D189	≤0.02	≤0.01
Acid value (mgKOH/g)	ASTM D664	≤0.8	n.a.
Copper strip corrosion (No.)	ASTM D130	≤3	≤1
Lubricating properties (wear scar, μm)	ASTM D6079	n.a.	≤460

n.a.: non-applied; TS: Thai standards; IS: International standards;
AED: Agricultural engine diesel; HSD: High-speed diesel.

The brake power, specific input fuel, brake-specific fuel consumption, and brake thermal efficiency were calculated the according to the following equation.

$$\text{P} = 0.746\ \text{BHP} \tag{3.11}$$

$$\text{BHP} = \frac{WN}{5000} \tag{3.12}$$

$$m^{\cdot} = \rho \text{v}^{\cdot} \tag{3.13}$$

$$\text{BSFC} = \frac{m^{\cdot}}{P} \tag{3.14}$$

$$\text{BTE} = \frac{3{,}600 * 100}{\text{BSFC} * \text{LHV}} \tag{3.15}$$

Definition

P = Brake power (kW)

BHP = Brake horse power (HP)

W = Torque (lbf.ft)

N = Speed (rpm)

$m^{\cdot}$ = Specific input fuel by mass (kg/hr)

ρ = Fuel density (kg/m^3)

$\mathrm{v}^{\cdot}$ = Specific input fuel by volume (m^3/hr)

BSFC = Brake specific fuel consumption (kg/kW-hr)

BTE = Brake thermal efficiency (%)

LHV = Low heating value (kJ/kg)

Figure 3.7 Diesel engine model KUBOTA RT100 DI Plus.

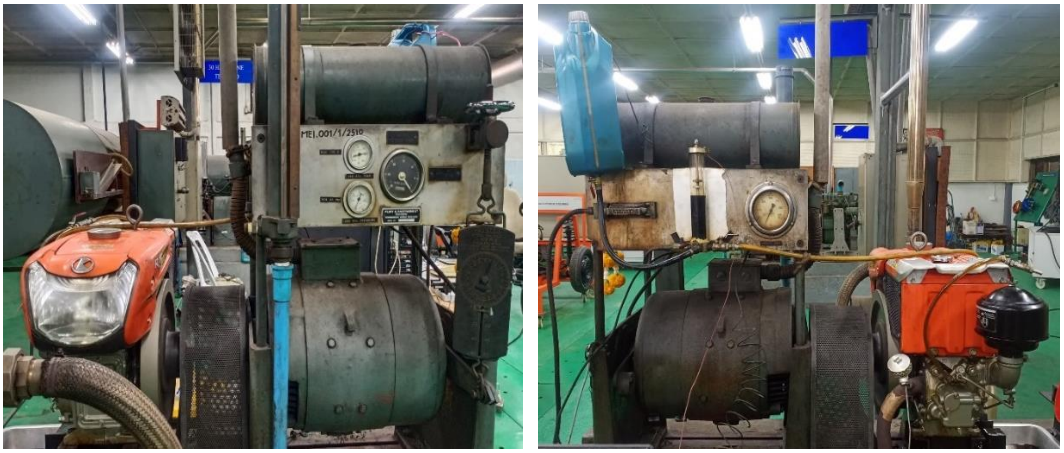


Figure 3.8 Engine performance test stand.

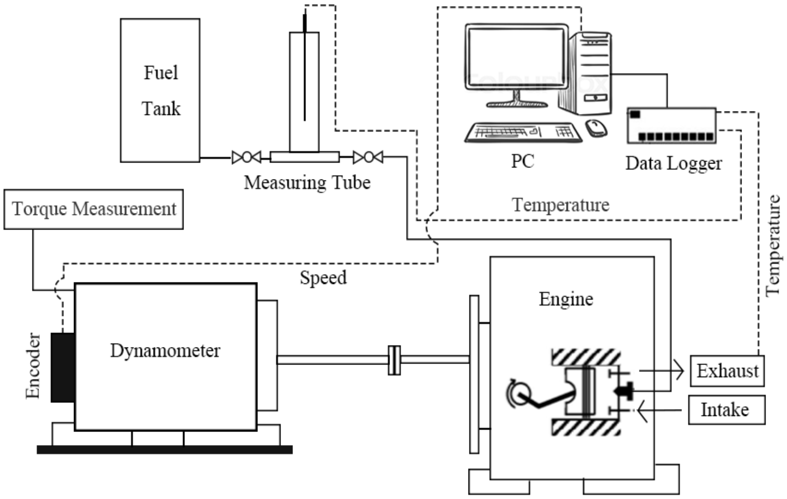


Figure 3.9 Diagram stand test engine performance.

3.4.2.2 Biodiesel properties analysis

The samples of biodiesel at best conditions were sent to the Office of Scientific Instrument and Testing sent for testing at the Mechanical Engineering Department and Chemical Engineering Department Faculty of Engineering Prince of Songkla University, Hat Yai Campus tested the properties of biodiesel. The analysis of such properties used different tools according to the list of properties and qualities of fatty acid methyl ester biodiesel according to the announcement of the Department of Energy Business.

3.5 Analysis of biodiesel production cost

In the production process need to calculate various costs in each step together with information to consider cost and cost-effectiveness as well as a guideline for development and practical use at the industrial level in the experiment to produce biodiesel from this palm fatty acid distillation section. This research used waste from the palm oil extraction process to produce energy by using palm fatty acid distillate (PFAD) as the main raw material for biodiesel production to add value and alternative methods of utilization. This test also focuses on studying the properties of biodiesel based on variables of interest to find out how to make the best use of this waste and maximize its value. The research calculates the cost of raw materials for production and electricity consumption by reading from the developed machines but this cost analysis does not analyze the cost of equipment and tools.

3.5.1 Raw material cost

The raw materials were focused for producing cost such as 1) PFAD 2) methanol and 3) sulfuric acid used in biodiesel production (PFAD of 25.88 baht/kg, methanol price 737.38 baht/20L, and sulfuric acid price 450 baht/2.5L as of April 1, 2022.).

3.5.2 Electricity cost

The electricity cost in the experiment and electricity cost of methanol recovery from Watt-hour meters and calculate electricity bill from an electricity rate of 4 baht per unit (Provincial Electricity Authority, 2015).

3.5.3 Total cost

The total cost of the biodiesel production experiment was due to the combination of the cost of raw materials and electricity costs used but not the cost of other equipment.

1) Cost of the microwave biodiesel per batch

$$\text{Biodiesel production cost (Baht/L)} = \frac{(\text{Materials cost} + \text{Chemical cost} + \text{Electricity cost})}{\text{Volume of biodiesel product}}$$

2) Cost of the microwave biodiesel per batch with methanol recovery cost

$$\text{Production cost (Baht/L)} = \frac{[(1)+\text{Electricity cost (MR)}]-\text{Volum of (MR)}}{\text{Volume of biodiesel product}}$$

MR = Methanol recovery

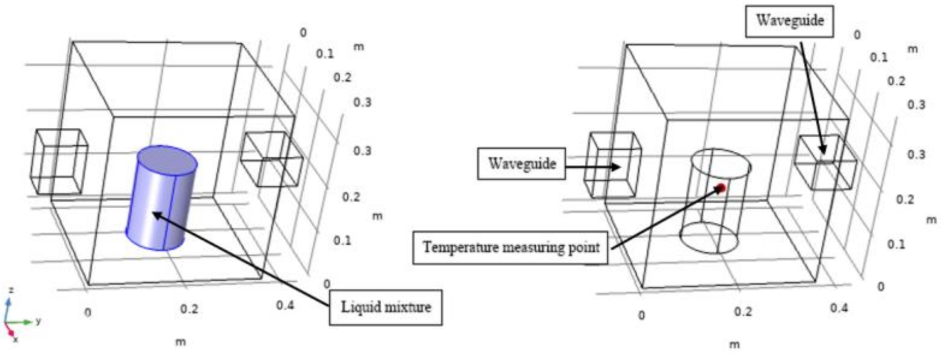
CHAPTER 4
RESULTS AND DISCUSSION

This research aims to study the optimum condition in biodiesel production from palm fatty acid distillate by esterification process by microwave heating, such as ratio PFAD to methanol as 1:7, 1:9, and 1:11 mole, reaction temperature of 70, 80, and 90 °C, reaction time as 20, 30, and 40 minutes, and amount of sulfuric acid as 2 wt.% and the properties and composition of biodiesel and engine performance testing. Therefore, show the results of the experiment and discuss the results as follows:

4.1 Design, concept, and method of development of microwave system for biodiesel production.

4.1.1 Microwave oven (cavity)

The microwave oven (cavity) consists of two microwave sources (magnetrons). The microwave oven is made of stainless steel measuring 312×352×360 mm. Multiple physics simulations were run to estimate the temperature temporarily in the liquid mixture under microwave heating using the COMSOL software package, Multiphysics demonstrated that the liquid mixture is in a laminar flow system and is considered a homogeneous single-phase solution. (Selemani 2018) The temperature-time profile in the liquid mixture was obtained using a thermocouple type-K pellet placed in the center of the reactor as shown in Figure 4.1



(a) (b)

Figure 4.1 (a) Microwave-assisted biodiesel conversion model, and (b) temperature measuring point.

The microwave oven (cavity) is used for filling the 2,000 ml Duane bottle and has a stainless-steel lid. Microwave oven lid and Duran bottle cap were punched 1 hole used to install thermocouples to bring data into the data collection system with a temperature controller.

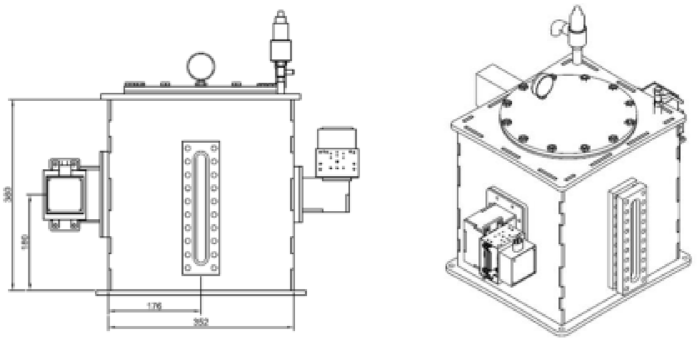


Figure 4.2 Microwave-assisted biodiesel conversion set up

4.1.2 Temperature control system

The microwave pyrolysis system will control the temperature by using a digital temperature controller brand SHIMAX model MAC3D-MSF-EN-NRN body size 48x48 mm. The input that can be used is a thermocouple type (K, J, T, E, R, S, U, N, B, Pr/RTD PT100/JPt 100 Voltage 0-10 mV, 0-20 mV, -10-10 mV, 0-50 mV, 0-100 mV, and two outputs, which are pulsed drives a 12VDC 20 mA solid state relay. Temperature data can be transmitted and recorded to a computer via RS485 during the experiment. Which is used in conjunction with the Shimax soft program. Start the temperature control system by installing a thermocouple type-K to measure temperature in a flask containing liquid. The digital temperature controller amplifies the signal from the thermocouple and reads the temperature to be able to control the temperature equal to 70, 80, and 90 °C, and install a solid-state relay (SSR) which acts as a switch. On-off circuit by using electromagnet was set as a switch to turn microwave power on and off. The temperature control during the experiment must be able to achieve the maximum and minimum temperature settings quickly and continuously.

4.1.3 Watt-hour meter system

The KEPLER brand Alianze Energy Pro Power Meter was used in this research. The electric energy meter is a device that displays the parameters and quantities of various electrical energy such as voltage, current, actual power, and reactive power, etc., to know the electrical value in the production process, and the use of electric power, both in controlling or improving the use of electricity to achieve full efficiency in working as well as to help manage energy.

Results of the process of developing a microwave biodiesel system by developing a microwave prototype for biodiesel production two microwave power systems (magnetrons) were installed along with an air-cooling system consisting of fans on stainless steel reactors. The prototype system is a biodiesel product from palm fatty acids distillate with microwave energy including the electrical control cabinet that powers the magnetron to convert electrical energy into microwave energy. The watt-hour meter is an indicator of the power consumption of the system. including installing a temperature control system as mentioned above the whole system is built on a stainless-steel structure supported by wheelbases. For ease of work, testing, including moving installation.

4.1.4 Microwave-assisted biodiesel system

From the design concepts and methods of development of the prototype system, a biodiesel product from palm fatty acids distillate with microwave energy is mentioned above. This made it possible to create a prototype of a biodiesel production system as shown in Figure 4.3.

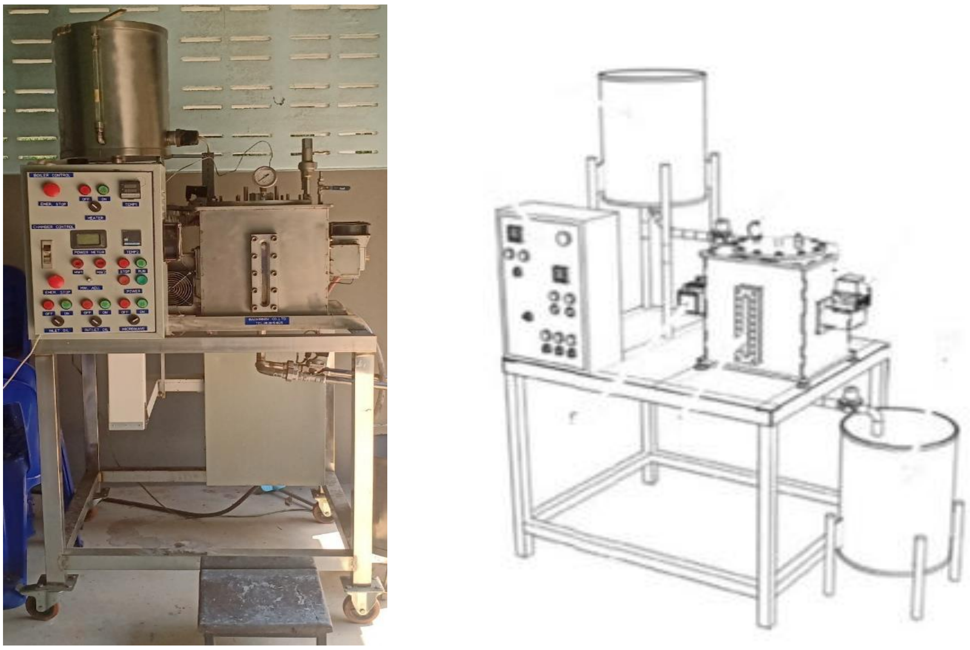


Figure 4.3 Microwave-assisted biodiesel system.

4.2 Test results prototype system a biodiesel product from palm fatty acids distillate with microwave energy preliminary by testing with tap water.

The preliminary test of the prototype system a biodiesel product from palm fatty acids distillate with microwave energy using tap water was observed. Microwave power calibration of the prototype system can determine the microwave power generated by the magnetron by calculating the power (P) of the heat-converting microwave wave from the equation (4.1).

$$P(Watt) = \frac{4.19 \times v \times \Delta T}{t} \qquad (4.1)$$

v is the volume in milliliters, ΔT is the temperature change in degrees celsius and, t is the time in seconds, therefore, to determine the microwave power of microwave-assisted biodiesel system it was generated by calculating the system power according to the equation (4.1). The microwave power calculation of microwave-assisted biodiesel system shown in Table 4.1.

Table 4.1 Calibration of microwave system

Run	Initial temperature of tap water T_0 (℃)	Final temperature of tap water T (℃)	Temperate difference $\Delta = T - T_0$ ℃	Microwave power of the system $P(Watt)$
1	31.6	78.2	23.0	1,300.76
2	31	75.9	28.3	1,253.31
3	31.2	76.3	41.7	1,258.89
average				1,270.99

From the experimental results shown in the Table 4.1, it was found that when testing the microwave power of the system by turning on magnetron position 1 and position 2 were found to be microwave power. The system average value was 1,270.99 Watts.

4.3 The results of the study on the characteristics of palm fatty acid distillate

The physical characteristics of PFAD are by product resulting from the distillation process. Crude palm oil refined bleached deodorized Palm Oil: RBD palm oil, which is a light brown solid at normal temperature, is used as a raw material in the oleochemical soap industry. Health industries, such as vitamin E production, include the production of biodiesel. Figure 4.4 shows the physical characteristics of PFAD.

Figure 4.4 Physical characteristics of PFAD.

Table 4.2 Property of PFAD

Property	Palm fatty acid distillate (PFAD)
Free fatty acid (%wt.)	97.29
Monoglyceride (%wt.)	0.22
Diglyceride (%wt.)	1.72
Triglyceride (%wt.)	0.78

Palm fatty acid distillate (PFAD) from by New Biodiesel Co., Ltd. The properties of raw PFAD were characterized by thin-layer chromatography (TLC; IATROSCAN MK-6s, SES Germany). It consisted of triglyceride (TG), diglycerides (DG), monoglycerides (MG), and free fatty acid (FFA) in the proportions of 0.78, 1.72, 0.22, and 97.29 wt.% respectively.

4.4 Optimizing microwave-assisted synthesis of biodiesel

Two responses, namely the maximum %FFA conversion and the minimum production cost (USD) were targeted by the experimental optimization using the Box–Behnken design, with the factors and their levels shown in Table 3.1. The %FFA conversion and cost responses, shown in Table 4.3, were obtained for 15 experimental runs. In the experimental results, first the temperature increased from the initial state to the setpoint temperature (70, 80, or 90 °C) during 2.47±0.40, 3.26±0.80, and 4.10±1.08min, respectively, while the average total power consumptions for producing MWBD fuel at these setpoints (70, 80, and 90 °C) were 0.21±0.07, 0.26±0.03, and 0.34±0.07kWh, respectively. The quadratic model fits to predict the %FFA conversion and the linear model fits to predict the cost, shown in equation (4.2)–(4.3).

Table 4.3 Experimental Box–Behnken design and results of the FFA conversion (%) response in MW-assisted biodiesel production (currency conversion 33.51baht/USD on April 1, 2022)

Run	Factor			%Conversion		Cost (USD)	
	Ratio (PFAD: MeOH)	Temperature (°C)	Time (minutes)	Experiment	Predicted	Experiment	Predicted
1	11	80	20	97.92	98.43	1.28	1.22
2	11	90	30	95.25	96.16	1.33	1.34
3	7	70	30	96.22	96.54	1.39	1.36
4	11	80	40	96.44	97.07	1.29	1.28
5	9	80	30	97.96	98.30	1.30	1.35
6	7	80	20	94.95	95.55	1.43	1.42
7	9	70	20	97.15	97.51	1.29	1.23
8	9	80	30	97.16	98.30	1.44	1.35
9	9	90	40	96.14	97.05	1.61	1.47
10	9	70	40	95.35	97.43	1.32	1.29
11	9	90	20	97.62	95.53	1.42	1.41
12	7	80	40	95.55	98.35	1.47	1.48
13	7	90	30	97.96	96.20	1.59	1.54
14	9	80	30	97.96	98.30	1.33	1.35
15	11	70	30	97.62	98.18	1.21	1.16

$$\text{FFA conversion (\%)} = 2.040+5.833R+1.610T+0.436t-0.021RT-0.052Rt+0.004Tt-0.133R\ 2 - 0.010T\ 2 -0.004t\ 2 \quad (4.2)$$

$$\text{Cost (USD)} = 0.972-0.048R+0.009T+0.003t \quad (4.3)$$

Here, R is the molar ratio of PFAD to methanol, T is the reaction temperature, and t is the reaction time. Analysis of variance of these regression models at the confidence level 95% ($\alpha = 0.05$) is shown in Table 4.4 The P-value was better than 0.05 for both regression models, which indicates the high significance of the models, while the coefficients of determination (R^2) and the adjusted coefficients of determination (R^2 adj) of %FFA conversion and cost (USD) were 0.9519, 0.8288, and 0.8654, 0.7821, respectively

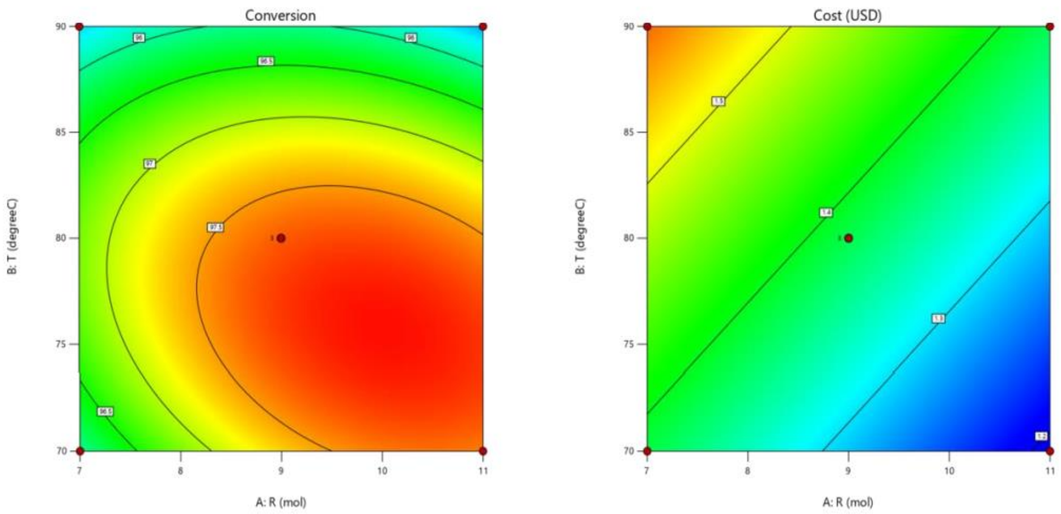
Table 4.4 ANOVA for the response surface regression models of conversion (%) and Cost (USD).

Source	**SS**	**df**	**MS**	**F-value**	**p-value**
Conversion (%):					
Model	14.98	9	1.66	11.00	0.0083
Residual	0.7563	5	0.1513		
Lack of Fit	0.3189	3	0.1063	0.4860	0.7262
Pure Error	0.4374	2	0.2187		
Total	15.74	14			
Cost (USD):					

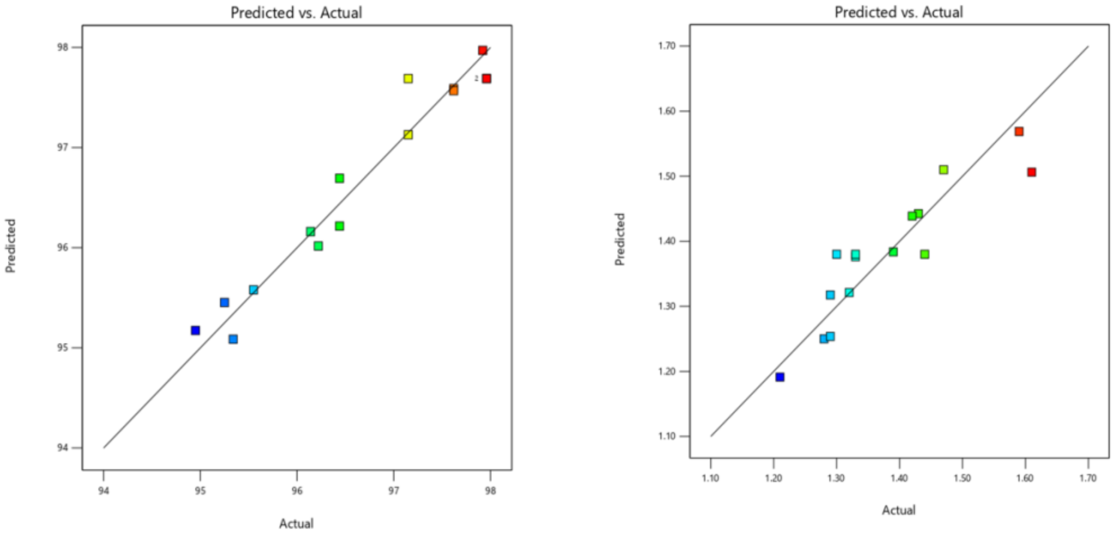
Model	0.1517	3	0.0506	17.75	0.0002
Residual	0.0313	11	0.0028		
Lack of Fit	0.0205	9	0.0023	0.4184	0.8530
Pure Error	0.0109	2	0.0054		
Total	0.1830	14			

Note SS = Sum of Square; MS = Mean sum of Square; and df = degree of freedom.

In the results, the time factor (t) was not significant, so the two-dimensional response surface contour plots of the two responses (%FFA conversion and cost) are shown in Figure. 4.5(a) and (b) only for the 20min process duration. The optimal operating point is shown by the red point in this figure: ratio (PFAD:MeOH) 1:9, and temperature 80 °C. The correlation between the predicted results from regression models and the actual experimental results in Table 5 is plotted in Figure. 4.5(c), (d). The plots show straight trend lines with R^2 = 0.9519 and 0.8654 for %FFA conversion and cost (USD), respectively. The MWBD conversion was tested under these candidate optimal conditions, and the product performance was then tested by using the single-cylinder diesel engine.



a) b)



c) d)

Figure 4.5 Two-dimensional response surface contour plots with ratio and temperature axes are shown in the top panel (a) and (b) and the correlation plots of actual (experimental) and model fit are shown on the bottom panel (c) and (d) for %conversion and cost (USD).

4.5 Temperature profile of the liquid mixture

The initial time profiles of temperature from simulations that were described above in the section on the simulation of the liquid mixture temperature profile are shown with the experimental results in Figure. 4.6, for the various mixtures labeled by molar ratio (R). The temperature increased rapidly, and more so when the molar ratio of PFAD to methanol was increased. This is because the complex relative permittivity of the liquid mixture increased with the ratio PFAD:MeOH. This affects heating by microwaves via the dielectric mechanisms, dipolar polarization and ionic conduction, which strongly affect the relative dielectric loss factor. Other key factors are electric field strength and the temperature of the material (Rosa, Veronesi et al. 2013, Sun, Wang et al. 2016).

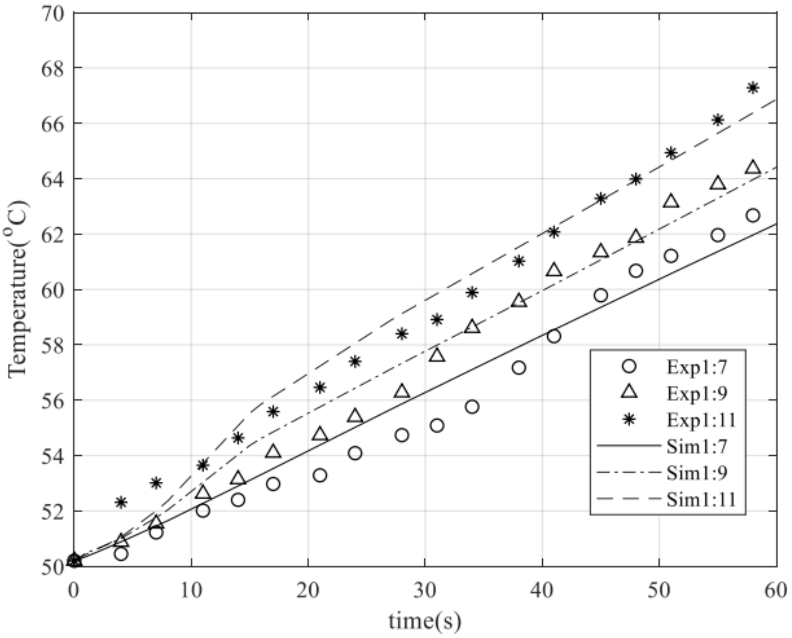


Figure 4.6 Temperature time profiles from simulations and experiments.

4.6 Fuel performance tested in a single cylinder diesel engine.

The properties of MWBD are summarized in Table 4.5. All the properties complied with Thai standards except for the DG and TG content, which exceeded the standard specifications. Biodiesel conversion in a two-stage process should therefore be tested, potentially to provide an improvement on this singlestage approach. The two-stage system is motivated by reducing operating costs, a lower alcohol ratio, reduced reaction time, and minimized yield losses (Thoai, Tongurai et al. 2019). The key properties of the three liquid fuels a pure MWBD, a liquid fuel blend (LFB, MWBD, CHSD 50:50 by volume), and a pure commercial high-speed diesel (CHSD) are summarized in Table 4.6. The cold flow properties, characterized by cloud and pour points, indicate the potential of diesel fuel for various climates, and the three cases met the Thai agricultural engine diesel (AED) and high-speed diesel (HSD) standards. They are all appropriate for a warm climate like that in Thailand. Another important flow property is viscosity, which affects fuel injection, atomization, combustion behavior, and engine performance and emissions. However, the MWBD had a dramatically higher viscosity than CHSD (+59.9%), and it was slightly higher than the upper regulatory limit of the Thai HSD standard (+22.4%) but still met the Thai AED standard. The properties indicating corrosive wear of diesel engine parts and fuel systems are acid value and copper strip corrosion. The MWBD had a low titrated acid value, while its copper strip corrosion was in category No. 1a, meaning low corrosive wear, and it met both Thai AED and HSD standards. This is because the PFAD was mainly composed of weakly acidic tail oil monoacid, which does not cause a high rate of corrosive wear (Eiadtrong, Maliwan et al. 2021) and HSD standards. The heating value stands for the direct energy content supplied to the engine. These values of MWBD and LFB were lower than that of the CHSD by -21.5% and -10.7%, respectively. The previous study (Eiadtrong, Maliwan et al. 2019) also found that biodiesel from PFAD had a slightly lower heating value than CHSD, by -12.8%. The last important property is the flash point, which relates to the safe storage and utilization of diesel fuel. It is the lowest temperature that will allow ignition when injected into an ignition source. The MWBD met both Thai AED and HSD standards for flashpoints, and it can be considered safe for use as diesel fuel.

Table 4.5 Properties of microwave heating biodiesel (MWBD).

M **Property**	**Test method**	**Thai standards**	**Test/Base fuel**
			MWBD
Water content (%wt.)	Karl Fisher	< 0.05	0.04
Oxidation stability at 110 ◦C	EN 15751	> 10	>24
Linolenic Acid Methyl Ester (%wt.)	EN 14103	< 12	0.296
Methanol (%wt.)	EN 14130	< 0.20	0.11
Methyl ester (%wt.)	EN 14103	< 96.5	95.95
Monoglyceride (%wt.)	EN 14105	< 0.70	0.28
Diglyceride (%wt.)		< 0.20	1.58
Triglyceride (%wt.)			2.8

MWBD = microwave- assisted biodiesel.

Table 4.6 Important properties of fuel.

Property	Test method	Thai standards of AED/HSD	Fuel		
			CHSD	**Biodiesel**	**LFB**
Cloud point (◦C)	ASTM D2500	n.a./n.a.	8	13	-
Pour point (◦C)	ASTM D97	n.a./<10	− 5	10	-
Kinematic viscosity at 40 ◦C (mm^2 /s)	ASTM D445	1.9–8.0/1.8–4.1	3.14	5.02	-
Acid value (mgKOH/g)	ASTM D664	≤0.80/n.a	0.05	0.055	-
Copper strip corrosion (No.)	ASTM D130	≤3/<1	1a	1a	-
Density at 15 ◦C (kg/dm^3)	ASTM D1298	860–900/810–870	832	879.9	846.95
Density at 30 ◦C (kg/dm^3)		n.a./n.a.	821.85	869.17	836.62
Higher heating value (kJ/kg)	ASDT D240	n.a./n.a.	44,900	35,262	40,081
Flashpoint (◦C)	ASTM D93	≥120/>52	69	137	-

n.a. = non applied; AED: Agricultural engine diesel; HSD: High speed diesel

The main objectives of this research section are to study the fuel applications of interest and assess the use of the fuel of interest on the test stand to assess whether the fuel of interest can be used in the engine without engine modifications. The study of fuel production from palm fatty acid distillation section found that it can be mixed with diesel fuel. This section of the study further explores the key fuel properties of biodiesel fuels of fuel of interest for the performance test of Kubota RT100 DI Plus engine with 3 test fuels: CHSD, MWBD, and LFB compared to diesel fuel were studied in this part of the research.

Various load changes at a constant speed torque of 2,200 rpm were tested, selected loads of 3.9, 7.8, 11.7, and 15.5 lbf. ft or (1.28, 2.56, 3.85, and 5.09 kW), respectively, recorded all the data from the test and all the data were calculated for braking power, specific input fuel, brake specific fuel consumption, and brake thermal efficiency.

4.6.1 Specific input fuel

In the experiment for engine running with different load changes at a constant speed torque of 2,200 rpm, to generate more braking power, a highe amount of fuel is injected into the combustion chamber while the amount of air entering the cylinder remains unchanged. The effect of the mass flow rate of the fuel supplied to the combustion chamber in terms of specific input fuel shows the fuel consumption rate as shown in Figure 4.7 overall fuel consumption of all fuels is approximately the same at all loads. It can be observed that every load (P = 1.28, 2.56, 3.85, and 5.09 kW) has a fuel consumption rate of MWBD and LFB slightly higher than diesel this corresponds to the work (Eiadtrong, Maliwan et al. 2021), which can be seen that the fuel consumption increases with the load. These characteristics are typical of diesel engines which correspond consistently with the research (Mompiboon and Leevijit 2011).

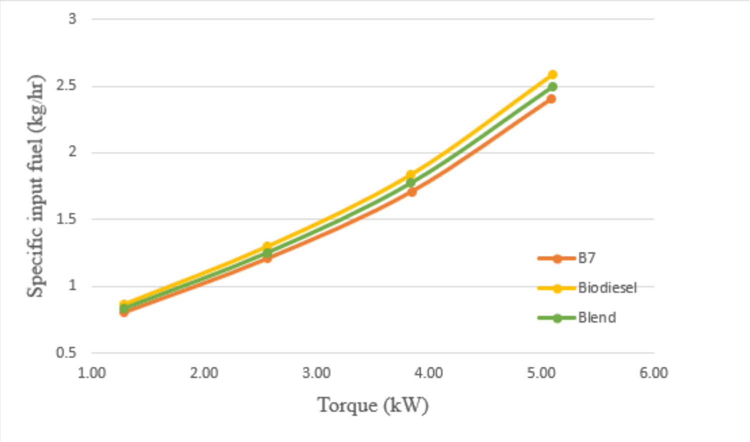


Figure 4.7 Engine-specific input fuel at various loads (speed of 2,200 rpm).

4.6.2 Brake-specific fuel consumption (BSFC)

For brake-specific fuel consumption when running the engine with 3 types of test fuels with different load changes at a constant speed torque of 2,200 rpm as shown in Figure 4.8 found that at low loads all fuels have brake-specific fuel consumption higher than other loads and its value decreases as the load increases. Comparing all three fuel types, the MWBD and LFB-powered engines have significantly more brake-specific fuel consumption than those with CHSD in every load which corresponds to the research (Mompiboon and Leevijit 2011, Eiadtrong, Maliwan et al. 2021).

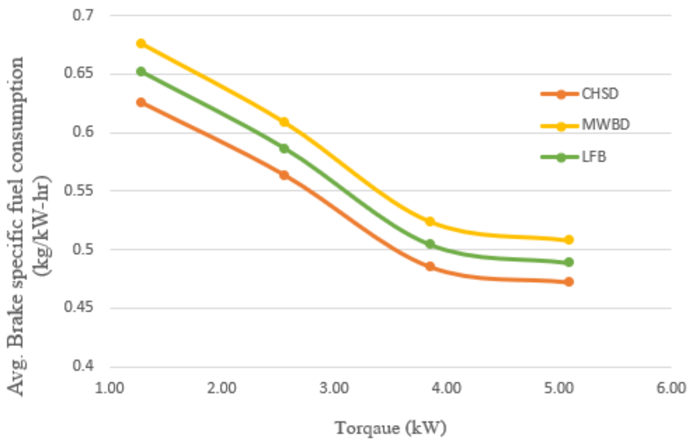


Figure 4.8 Engine brake-specific fuel consumption at various loads (speed of 2,200 rpm).

4.6.3 Brake thermal efficiency (BTE)

As for the brake thermal efficiency of the engine for running the engine by the load change method, as shown in Figure 4.9. It can be seen that when the load is increased, the brake thermal efficiency of the engine will increase accordingly, with the engine's brake thermal efficiency being the highest at 3.84 kW load of the engine walking with MWBD and LFB as for the engine running at a constant speed of 2,200 rpm, the engine's brake thermal efficiency is the highest. Comparing the three test fuels, the MWBD and LFB-powered engines had more brake thermal efficiency than the CHSD-powered engines, consistent with the research (Mompiboon and Leevijit 2011, Eiadtrong, Maliwan et al. 2021).

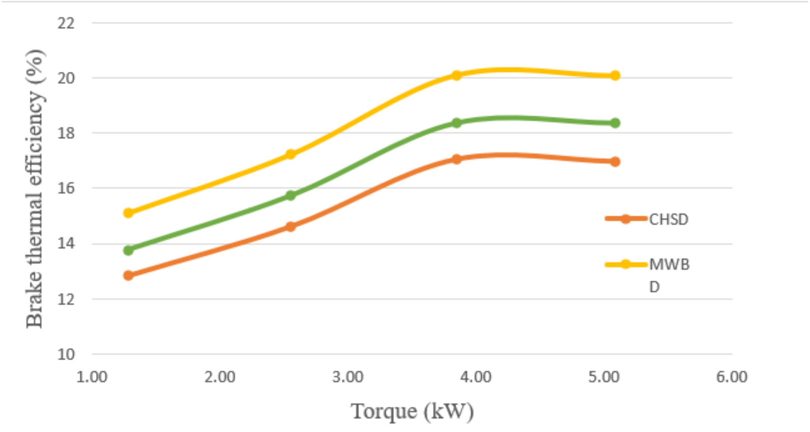


Figure 4.9 Engine brake thermal efficiency at various loads (speed of 2,200 rpm).

The most important engine performance results are the average brake-specific fuel consumption (BSFC) and the average brake thermal efficiency (BTE). The BSFC reflects the combustion engine's efficiency in producing mechanical power, and on the other hand, the BTE is a fundamental quantity (unitless bare number). Normally, there are considered indexes to compare with a theoretical value. The BSFC with various loads at the fixed rotation speed torque at 2,200 rpm. The BSFC of MWBD and LFB were generally higher than that of CHSD over almost all of the conditions tested; moreover, the BSFC slightly increased with the proportion of MWBD. Similar results have been reported for various diesohols because the liquid fuel blend generally has a slightly lower heating value than CHSD. Also, the results in terms of energy efficiency are seen in Figure 4.9. The brake thermal efficiency (BTE) of MWBD and LFB was higher than that of CHSD in all conditions tested, and the improvement gap in BTE increased at high operating loads. The brake thermal efficiency (BTE) seen for various liquid fuel blends (like anhydrous butanol-based diesohol) is better than that for diesel also in previous studies.

The most important engine performance results, the average brake specific fuel consumption (BSFC) and the average brake thermal efficiency (BTE), are shown in Figure (4.8)-(4.9), in the top and the bottom panels, respectively. The BSFC reflects the combustion engine’s efficiency in producing mechanical power, and on the other hand, the BTE is a fundamental quantity (unitless bare number). Normally, these are considered indexes for comparison with a theoretical value. The BSFC with various loads at the fixed rotation speed at 2200 rpm can be seen in the top panel of Figure 4.9. The BSFCs of MWBD and LFB were generally higher than that of CHSD over almost all of the conditions tested; moreover, the BSFC increased slightly with the proportion of MWBD. Similar results have been reported for various diesohols, because the liquid fuel blend generally has slightly lower heating value than CHSD 25–30. The results in terms of energy efficiency are as show in Figure 4.9. The BTEs of MWBD and LFB were higher than that of CHSD in all conditions tested, and the improvement gap in BTE increased at high operating loads. The BTEs seen for various liquid fuel blends (like anhydrous n-butanol-based diesohol) were also better than that for diesel in previous.

The behavior of burning each type of fuel in the engine compartment depends on the properties of each type of fuel, such as cetane value, viscosity, and density when considering the cetane value high cetane fuel ignition delay period is low fuel can ignite quickly when the piston moves to the top dead center, resulting in higher engine braking efficiency for heavy fuels, high density when injecting fuel. The fuel will not disperse in the air after incomplete combustion. This reduces the thermal efficiency of the engine.

Therefore, the most important of the experimental results clearly showed that the free fatty acid blend from the distilled palm wax fraction is a molecule similar to the fatty acid ester. Not affect engine performance but a slight improvement in performance for the effect of improved engine performance was also seen in several studies testing biodiesel-diesel blends (Ramadhas, Muraleedharan et al. 2005, Muralidharan and Vasudevan 2011, Kiatkittipong, Phimsen et al. 2013, Sanli, Canakci et al. 2015, Nalgundwar, Paul et al. 2016).

4.7 Cost analysis of biodiesel production

Biodiesel production from microwave-assisted biodiesel system to analyze the total cost of biodiesel production was raw material cost, electricity cost, and total cost. Table 4.3 show the microwave-assisted biodiesel system.

Cost of biodiesel production from microwave refined palm oil in the case of using AC electricity, the ratio is 1:7 mol, total cost 1.39-1.59 USD/batch, ratio 1:9 mol total cost 1.29-1.61 USD/batch, and at 1:11 mol ratio, total cost 1.21-1.28 USD/batch (due to different reaction times resulting in a change in electricity cost).

CHAPTER 5

CONCLUSION AND SUGGESTION

5.1 Conclusion

The MWBD conversion of PFAD by esterification was performed in a batch reactor with two microwave sources (magnetrons). The experiments for response surface modeling followed a Box–Behnken design. The optimal conditions giving maximum %FFA conversion at a minimum cost (USD) had molar ratio (PFAD:methanol) 1:9, temperature 80 °C, and duration 20 min. The regression models that forecast %FFA conversion and cost (USD) fit the experimental results with coefficients of determination (R^2) at 0.9519 and 0.8654, respectively. The time profiles of the temperature at the center of the reactor were simulated with the FEM, using molar-averaged material properties, and they matched the experimental results well. The MWBD conversion under the model-predicted optimal conditions was tested, and the resulting fuel was blended with CHSD 50:50 by volume (liquid fuel blended = LFB). The most important fuel properties of MWBD, LFB, and CHSD met both Thai AED and HSD standards. All these liquid fuels performed well when tested in a single-cylinder diesel engine, being similar to each other in performance.

5.2 Suggestions

This study is the study of biodiesel production from the developed system. Using the heat from the microwave to determine the optimal value for biodiesel production, according to several studies, the most efficient range of biodiesel is at a 1:7-1:9 mole ratio of increasing factors to get biodiesel with higher efficiency.

In this research, it was revealed that the optimal ratio for biodiesel production was 1:9 mol, which was similar to other research is like this Since alcohol is a polar molecule when using a microwave will cause more heat the higher the ratio the reaction will be complete but another reason to use a larger ratio. It may be due to the loss of alcohol during the reaction. If further studies are needed to reduce the loss of alcohol during the reaction should reduce the ratio.

In the production of biodiesel, many other factors affect the production of biodiesel production such as reaction ratio, reaction temperature, reaction time, as well as the type and amount of catalyst, and heating power source which can be further studied using the same method as this research to find the appropriate value of various factors.

REFERENCES

Abdul Kapor, N. Z., G. P. Maniam, M. H. A. Rahim and M. M. Yusoff (2017). "Palm fatty acid distillate as a potential source for biodiesel production-a review." Journal of Cleaner Production **143**: 1-9.

Abubakar, Z., A. A. Salema and F. N. Ani (2013). "A new technique to pyrolyse biomass in a microwave system: Effect of stirrer speed." Bioresource Technology **128**: 578-585.

Athar, M. and S. Zaidi (2020). "A review of the feedstocks, catalysts, and intensification techniques for sustainable biodiesel production." Journal of Environmental Chemical Engineering **8**(6): 104523.

Attanatho, L., S. Magmee and P. Jenvanitpanjakul (2004). "Factors Affecting the Synthesis of Biodiesel from Crude Palm Kernel Oil."

Chen, G., R. Shan, J. Shi, C. Liu and B. Yan (2015). "Biodiesel production from palm oil using active and stable K doped hydroxyapatite catalysts." Energy Conversion and Management **98**: 463-469.

Chozhavendhan, S., M. Vijay Pradhap Singh, B. Fransila, R. Praveen Kumar and G. Karthiga Devi (2020). "A review on influencing parameters of biodiesel production and purification processes." Current Research in Green and Sustainable Chemistry **1-2**: 1-6.

Ciolkosz, D. (2020). Chapter 37 - What's so different about biodiesel fuel? Bioenergy (Second Edition). A. Dahiya, Academic Press: 739-744.

Domínguez, A., J. A. Menéndez, Y. Fernández, J. J. Pis, J. M. V. Nabais, P. J. M. Carrott and M. M. L. R. Carrott (2007). "Conventional and microwave induced pyrolysis of coffee hulls for the production of a hydrogen rich fuel gas." Journal of Analytical and Applied Pyrolysis **79**(1): 128-135.

Eiadtrong, S., K. Maliwan, G. Prateepchaikul, T. Kattiyawan, P. Thephsorn and T. Leevijit (2019). "Preparation, important fuel properties, and comparative use of un-preheated palm fatty acid distillate-diesel blends in a single cylinder diesel engine." Renewable Energy **134**: 1089-1098.

Eiadtrong, S., K. Maliwan, T. Theppaya, T. Kattiyawan, G. Prateepchaikul and T. Leevijit (2021). "An investigation to utilize ternary diesel-palm fatty acid distillate-10 wt% n-butanol blends as simply novel diesel substitutes." Fuel **289**: 119965.

Energy, E. P. a. P. O. M. o. (May 2022). "Oil price situation."

Falciglia, P. P., P. Roccaro, L. Bonanno, G. De Guidi, F. G. A. Vagliasindi and S. Romano (2018). "A review on the microwave heating as a sustainable technique for environmental remediation/detoxification applications." Renewable and Sustainable Energy Reviews **95**: 147-170.

Gebremariam, S. and J. Marchetti (2017). "Biodiesel production technologies: Review." AIMS Energy **5**: 425-457.

He, B. and J. V. Gerpen (2015). "Reactors for Biodiesel Production." National Institute of Food and Agriculture.

Hidayat, A., Rochmadi, K. Wijaya, A. Nurdiawati, W. Kurniawan, H. Hinode, K. Yoshikawa and A. Budiman (2015). "Esterification of Palm Fatty Acid Distillate with High Amount of Free Fatty Acids Using Coconut Shell Char Based Catalyst." Energy Procedia **75**: 969-974.

Hosseini, S., J. Janaun and T. S. Y. Choong (2015). "Feasibility of honeycomb monolith supported sugar catalyst to produce biodiesel from palm fatty acid distillate (PFAD)." Process Safety and Environmental Protection **98**: 285-295.

Karmakar, B. and G. Halder (2019). "Progress and future of biodiesel synthesis: Advancements in oil extraction and conversion technologies." Energy Conversion and Management **182**: 307-339.

Kiatkittipong, W., S. Phimsen, K. Kiatkittipong, S. Wongsakulphasatch, N. Laosiripojana and S. Assabumrungrat (2013). "Diesel-like hydrocarbon production from hydroprocessing of relevant refining palm oil." Fuel Processing Technology **116**: 16-26.

REFERENCES (CONTINUED)

Lee, K. and C. Ofori-Boateng (2013). Sustainability of Biofuel Production from Oil Palm Biomass.

Lee, X. J., L. Y. Lee, S. Gan, S. Thangalazhy-Gopakumar and H. K. Ng (2017). "Biochar potential evaluation of palm oil wastes through slow pyrolysis: Thermochemical characterization and pyrolytic kinetic studies." Bioresource Technology **236**: 155-163.

Loupy, A., L. Perreux, M. Liagre, K. Burle and M. Moneuse (2001). "Reactivity and selectivity under microwaves in organic chemistry. Relation with medium effects and reaction mechanisms." Pure and Applied Chemistry.

Lucena, I. L., G. F. Silva and F. A. N. Fernandes (2008). "Biodiesel Production by Esterification of Oleic Acid with Methanol Using a Water Adsorption Apparatus." Industrial & Engineering Chemistry Research **47**(18): 6885-6889.

Ma, F. and M. A. Hanna (1999). "Biodiesel production: a review1Journal Series #12109, Agricultural Research Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln.1." Bioresource Technology **70**(1): 1-15.

Majetich, G. and R. Hicks (1995). "The Use of Microwave Heating To Promote Organic Reactions." Journal of Microwave Power and Electromagnetic Energy **30**(1): 27-45.

Malvade, A. and S. Satpute (2013). "Production of Palm Fatty Acid Distillate Biodiesel and Effects of its Blends on Performance of Single Cylinder Diesel Engine." Procedia Engineering **64**.

Malvade, A. V. and S. T. Satpute (2013). "Production of Palm Fatty Acid Distillate Biodiesel and Effects of its Blends on Performance of Single Cylinder Diesel Engine." Procedia Engineering **64**: 1485-1494.

Mat Yasin, M. H., R. Mamat, G. Najafi, O. M. Ali, A. F. Yusop and M. H. Ali (2017). "Potentials of palm oil as new feedstock oil for a global alternative fuel: A review." Renewable and Sustainable Energy Reviews **79**: 1034-1049.

Meher, L. C., V. S. S. Dharmagadda and S. N. Naik (2006). "Optimization of alkali-catalyzed transesterification of Pongamia pinnata oil for production of biodiesel." Bioresource Technology **97**(12): 1392-1397.

Metre, A. and K. Nath (2015). "Palm fatty acid distillate based biodiesel: Characterization and emission analysis." **74**: 584-588.

Mishra, R. R. and A. K. Sharma (2016). "Microwave–material interaction phenomena: Heating mechanisms, challenges and opportunities in material processing." Composites Part A: Applied Science and Manufacturing **81**: 78-97.

Mompiboon, P. and T. Leevijit (2011). "Fluidity Characteristics of Fuel Produced from Mixed Crude Palm Oil Blended with Diesel." PSU Knowledge Bank.

Motasemi, F. and F. N. Ani (2012). "A review on microwave-assisted production of biodiesel." Renewable and Sustainable Energy Reviews **16**(7): 4719-4733.

Muralidharan, K. and D. Vasudevan (2011). "Performance, emission and combustion characteristics of a variable compression ratio engine using methyl esters of waste cooking oil and diesel blends." Applied Energy **88**(11): 3959-3968.

Mutyala, S., C. Fairbridge, J. R. J. Paré, J. M. R. Bélanger, S. Ng and R. Hawkins (2010). "Microwave applications to oil sands and petroleum: A review." Fuel Processing Technology **91**(2): 127-135.

Nakorn, J. N. (2005). "Characterization of Crude Palm Oil Produced from Satoon Province and its Stearin Fractionated by Centrifugation at Different Medium Solvents." PSU Knowledge Bank

Nalgundwar, A., B. Paul and S. K. Sharma (2016). "Comparison of performance and emissions characteristics of DI CI engine fueled with dual biodiesel blends of palm and jatropha." Fuel **173**: 172-179.

Pair, K. (2018). "Manufacturing cost."

REFERENCES (CONTINUED)

Phasinam, K., K. Nikhomchaiprasert, W. Arjharn and T. Kassanuk (2021). "PERFORMANCE AND WEARING OF A DIESEL ENGINE WITH BLENDS OF BIODIESEL AND HIGH SPEED DIESEL." Life Sciences and Environment Journal **22**(1): 48-61.

Popescu, S., T. Misawa, Y. Ohtsu, H. Fujita and S. Sanematsu (2008). "New microwave reactor for paper-based waste neutralization." Resources, Conservation and Recycling **52**(4): 671-677.

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

Rosa, R., P. Veronesi and C. Leonelli (2013). "A review on combustion synthesis intensification by means of microwave energy." Chemical Engineering and Processing: Process Intensification **71**: 2-18.

Ryniecki, A., J. Wawrzyniak and A. Pilarska (2015). "Basics of process: the on-off control system." Food Industry **11**: 26-29.

Salema, A. A. and F. N. Ani (2011). "Microwave induced pyrolysis of oil palm biomass." Bioresource Technology **102**(3): 3388-3395.

Sanli, H., M. Canakci, E. Alptekin, A. Turkcan and A. N. Ozsezen (2015). "Effects of waste frying oil based methyl and ethyl ester biodiesel fuels on the performance, combustion and emission characteristics of a DI diesel engine." Fuel **159**: 179-187.

Selemani, A. (2018). "Thermal chemical enhancement and influence of fluid flow in transesterification of palm oil." Energy Sources, Part A: Recovery, Utilization, and Environmental Effects **40**(1): 81-87.

Shahir, V. K., C. P. Jawahar and P. R. Suresh (2015). "Comparative study of diesel and biodiesel on CI engine with emphasis to emissions—A review." Renewable and Sustainable Energy Reviews **45**: 686-697.

Shemelis Nigatu, G. and M. Jorge Mario (2017). "Biodiesel production technologies: review." AIMS Energy **5**(3): 425-457.

Shuit, S. H. and S. H. Tan (2014). "Feasibility study of various sulphonation methods for transforming carbon nanotubes into catalysts for the esterification of palm fatty acid distillate." Energy Conversion and Management **88**: 1283-1289.

Sun, J., W. Wang and Q. Yue (2016). "Review on Microwave-Matter Interaction Fundamentals and Efficient Microwave-Associated Heating Strategies." Materials **9**(4).

Tang, J. (2015). "Unlocking Potentials of Microwaves for Food Safety and Quality." Journal of Food Science **80**(8): E1776-E1793.

Thoai, D. N., C. Tongurai, K. Prasertsit and A. Kumar (2019). "Review on biodiesel production by two-step catalytic conversion." Biocatalysis and Agricultural Biotechnology **18**: 101023.

Undri, A., M. Abou-Zaid, C. Briens, F. Berruti, L. Rosi, M. Bartoli, M. Frediani and P. Frediani (2015). "Bio-oil from pyrolysis of wood pellets using a microwave multimode oven and different microwave absorbers." Fuel **153**: 464-482.

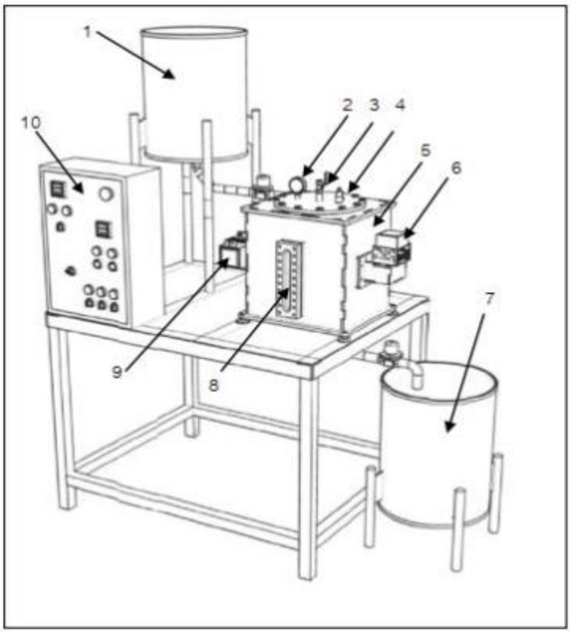
Vasudevan, P. T. and M. Briggs (2008). "Biodiesel production—current state of the art and challenges." Journal of Industrial Microbiology and Biotechnology **35**(5): 421-421.

Wong, K. Y., J.-H. Ng, C. T. Chong, S. S. Lam and W. T. Chong (2019). "Biodiesel process intensification through catalytic enhancement and emerging reactor designs: A critical review." Renewable and Sustainable Energy Reviews **116**: 109399.

Xu, H., U. Lee and M. Wang (2020). "Life-cycle energy use and greenhouse gas emissions of palm fatty acid distillate derived renewable diesel." Renewable and Sustainable Energy Reviews **134**: 110144.

Yin, C. (2012). "Microwave-assisted pyrolysis of biomass for liquid biofuels production." Bioresource Technology **120**: 273-284.

APPENDIX A



1) Product preparation tank
2) Pressure gauge
3) Pressure reducing channel
4) Thermocouple inserts channel
5) Reactor Tank
6) The first magnetron
7) Product storage tank
8) See-through channel
9) The second magnetron
10) System electrical control box

Figure A1. Microwave-assisted biodiesel system.

Figure A2. System electrical control box.

Figure A3. Physical characteristics of PFAD before melt.

Figure A4. Physical characteristics of PFAD after melt.

Figure A5. Warm repel water.

Figure A6. Rinse with warm.

Figure A7. Rotary evaporator.

Original Article

Biofpr
Biofuels Bioproducts & Biorefining

Microwave-assisted biodiesel conversion of palm fatty acid distillate with performance tests in a single-cylinder diesel engine

Enarm Promnonsri, Major in Energy Technology, Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University Hatyai Campus, Hat-Yai, Thailand
Yutthapong Pianroj, Integrated High-Value Oleochemical Research Center, Prince of Songkla University Suratthani Campus, Muang, Thailand; Faculty of Science and Industrial Technology, Prince of Songkla University Suratthani Campus, Muang, Thailand
Teerasak Punvichai, Integrated High-Value Oleochemical Research Center, Prince of Songkla University Suratthani Campus, Muang, Thailand; Faculty of Innovation Agriculture and Fisheries Establishment Project, Prince of Songkla University Suratthani Campus, Muang, Thailand
Seppo Karrila, Faculty of Science and Industrial Technology, Prince of Songkla University Suratthani Campus, Muang, Thailand
Theerayut Leevijit, Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Hatyai Campus, Hat-Yai, Thailand
Sopida Sungsoontorn, Department of Mechanical Engineering, Faculty of Engineering, Rajamangaha University of Technology Rattanakosin, Nakhon Pathom, Thailand
Saysunee Jumrat, Integrated High-Value Oleochemical Research Center, Prince of Songkla University Suratthani Campus, Muang, Thailand; Faculty of Science and Industrial Technology, Prince of Songkla University Suratthani Campus, Muang, Thailand

Received July 13 2022; Revised August 30 2022; Accepted September 15 2022;
View online at Wiley Online Library (wileyonlinelibrary.com);
DOI: 10.1002/bbb.2439; *Biofuels, Bioprod. Bioref.* (2022)

Abstract: A batch microwave-assisted biodiesel (MWBD) conversion system was scaled up to using two magnetrons, giving a total of 2000 W microwave (MW) power, with the magnetrons placed asymmetrically on opposite sides of the MW cavity. This system was used to produce methyl ester from palm fatty acid distillate (PFAD). The response surface method with a Box–Behnken experimental design was applied to find the optimal point giving the maximum percentage free fatty acid (FFA) conversion at the minimum cost (USD). At this point the molar ratio PFAD:MeOH was 1:9; the temperature was 80 °C; and time was 20 min. Regression models predicted the %FFA conversion and the cost (USD) with coefficients of determination (R^2) of 0.9519 and 0.8654, respectively. Simulations were conducted with the finite element method, and the temperature profiles from the simulations fitted the experimental data well. Finally,

---

Correspondence to: Saysunee Jumrat, Integrated High-Value Oleochemical Research Center, Prince of Songkla University Suratthani Campus, 31 Moo 6, Muang, Surat-Thani 84000, Thailand. E-mail: saysunee.j@psu.ac.th

the fuel properties of the MWBD were analyzed and compared with Thai agricultural engine diesel and high-speed diesel standards, and the standards were met. The MWBD, the liquid fuel blend (LFB with MWBD:CHSD 50:50 by volume), and a commercial high-speed diesel (CHSD) were tested in a diesel engine over the 1.28–5.09 kW power range at a fixed 2200 rpm speed. All the fuels performed similarly and without any problems in the test runs. © 2022 Society of Chemical Industry and John Wiley & Sons, Ltd.

Key words: microwave-assisted biodiesel; palm fatty acid distillate; diesel substitute; diesel engine testing

Introduction

Nowadays the demand for energy and the issue of global warming are hot political and technical topics. Energy demand is increasing, with fossil fuels needed for combustion engines, households, industrial production, and services. Greenhouse gases are therefore emitted into the environment, affecting the atmosphere and the energy balance of our planet. To address concerns about this, technologies for the reduction of greenhouse gas emissions and alternative energy sources are sought.

Biodiesel is among the many promising alternative and renewable fuels, and might partly or fully substitute for fossil-fuel-based diesel. Biodiesel use contributes to cleaner air, carbon neutrality, and sustainability.[1]

The Thai government has a policy of encouraging the production and use of biodiesel. Thailand is the third largest palm oil producer in the world. In 2020, its production of crude palm oil (CPO) was 2.9 million tons. The CPO is mostly refined into vegetable oil, and the processing generates palm fatty acid distillate (PFAD) as a by-product at a rate of about 3.25% relative to CPO.[2] From a CPO production of 2.9 million tons of refined palm oil per year, we can then estimate that about 0.095 million tons per year of PFAD is generated. This large quantity and its potential for value-added processing make PFAD an attractive renewable raw material for conversion to biodiesel as an alternative fuel. Moreover, recent breakthroughs have enabled the catalytic conversion of some waste/low-cost renewable energy source materials, such as waste cooking oil, glycerol, and lignocellulosic biomass, to biodiesel, and bioethanol, as shown in Khodadadi *et al.*,[3] Costa *et al.*, [4] and Su *et al.*, [5] respectively.

Biodiesel is a clean alternative energy source – a renewable source of natural concentrated energy. It is also important because it can replace fossil fuels, reducing dependence on them, and can reduce emissions from combustion engines. It can be produced from natural renewable energy sources such as greases, animal fats, vegetable oils, and used cooking oil.[6] It consists of long-chain alkyl esters such as ethyl ester, methyl ester, or propyl ester,[7] and from fatty acids, which are organic triglycerides synthesized through esterification reactions between vegetable oil or animal fat and alcohol. Palm fatty acid distillate has a comparatively high (93%) free fatty acid (FFA) content, which can be converted into fatty acid methyl ester (FAME) by esterification using methanol (MeOH) and acid catalyst.[2,8] A good review of biodiesel production using PFAD as a source can be found in Abdul *et al.*[2] Natthapon and Krit[9] have reported a single-step process to produce biodiesel from PFAD and MeOH with the following esterification conditions: MeOH-to-oil molar ratio 8:3; H_2SO_4 catalyst 9.4 wt%; reaction time 92 min; reaction temperature 60 °C. Metre and Nath[10] report 12:1; 9 wt% super phosphoric acid, 300 min and 70 °C. Kanjaikaew *et al.*[11] used PFAD, MeOH, and H_2SO_4 catalyst in a two-step process to improve the biodiesel properties. In the first step they had a 4:1 molar ratio, 80 °C, and 15 min, resulting in 88 % FFA conversion; and the second step reached 86.8% under these conditions: 27:1 molar ratio, 53 min and 35.3 wt% catalyst amount. Under these two sets of optimal conditions, the overall %FFA conversion was 98.44.

Microwaves (MW) have been studied extensively for their ability to complete chemical reactions in very short times; moreover, there are other advantages to microwave processing, such as rapid heating (saving energy, time, and workspace), cost savings, precise and controlled processing, selective heating, and volumetric uniform heating.[12] Athar *et al.*[13] found the maximum yield of biodiesel from jatropha oil by using a central composite rotatable experimental design with response surface methodology (RSM) to optimize MW heating, giving 61.10% under the 11:7 molar ratio of the methanol to oil, 2 wt% sulfuric acid catalyst concentration, and a 90 min reaction time. Pham *et al.*[14] applied RSM with a central composite design to optimize reaction parameters in the microwave-assisted conversion of Tra and Basa catfish oils to biodiesel with acetone and isopropanol co-solvent, and they report prediction formulas for biodiesel yield with the coefficients of determination (R^2) 0.9926, and 0.9891, respectively. Gupta and Rathod[8] presented the utilization of solar energy with the help of the Fresnel lens solar concentrator (FSC) in the esterification of PFAD, and they found the highest conversion of 96.81% was achieved at a molar ratio of 8:1, catalyst dosage of 1.25 wt%, stirring speed of 200 rpm, reaction temperature of 62 °C, molecular sieves at 6 wt%, and reaction time of 30 min in their FSC approach.

Many methodologies, liquid solution mixes, heating techniques, and optimal conditions have been reported in previous studies but the previous papers have not assessed important biodiesel fuel properties or provided comparative results on engine performance. This study therefore scaled up batch microwave-assisted biodiesel (MWBD) conversion to a reactor capacity of 2000 mL and to two magnetrons for 2000 W of total power (each providing 1000 W). The response surface method with a Box–Behnken experimental design was used to estimate the optimal point regarding two responses: the maximum %FFA conversion and the minimum cost (USD). The liquid mixture temperature profiles were simulated numerically with the finite element method (FEM), and compared with the experimental results. Finally, the candidate optimal conditions of MWBD conversion were applied and the biodiesel was tested for important properties, along with its blend with commercial high-speed diesel (CHSD). The engine performance tests used a single-cylinder diesel engine.

Materials and methods

Materials

Palm fatty acid distillate was supplied by New Biodiesel Co., Ltd, located at Tha-Chang district of Suratthani province, Thailand. The properties of raw PFAD were characterized by thin-layer chromatography (TLC) (Iatroscan MK-6s, SES GmbH, Bechenheim / Germany). It consisted of triglyceride (TG), diglyceride (DG), monoglycerides, and free fatty acids (FFA) in the proportions 0.78, 1.72, 0.22, and 97.29 wt%, respectively. Methanol solution is from MODERN CHEMICAL Co., Ltd. (Sukhumvit, BANGKOK) was of commercial grade with 99.85% purity, and sulfuric acid (LOBA Chemie PVT., Ltd., Mumbai, INDIA) was of analytical reagent (AR) grade with 98% concentration. Further materials used were *n*-hexane, KOH pellets (LOBA Chemie PVT., Ltd. (Mumbai, INDIA)), and the certified reference material for free-FAME.

Experimental set-up

Batch MWBD conversion system

The system consisted of two magnetrons placed on rectangular waveguides, which were located on opposite sides of the cavity asymmetrically,[15–17] as shown in Fig. 1. The waveguides were operated in transverse electric field (TE_{10}) mode. These magnetrons operated at 2.45 GHz frequency and each was rated for a maximum power of 1000 W. They were connected to a microwave (MW) switching mode power supply (Enbiens: YB-MP1000). The temperature was controlled by the Shimax™ Co.,Ltd model MAC3D-MSF-EN-NRN temperature controller, which was connected to a type-K thermocouple. A Duran 2000 mL glass bottle was used as the reactor and was placed inside the MW cavity. The cavity had the dimensions 312 × 352 × 360 mm.

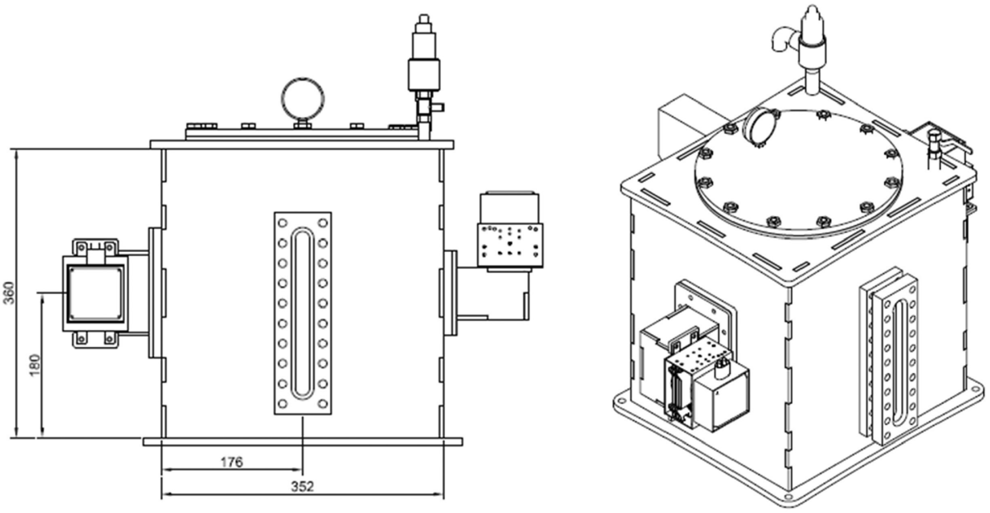


Figure 1. Microwave-assisted biodiesel conversion setup.

Esterification of PFAD with methanol

The Box–Behnken experimental design was used to optimize the %FFA conversion with three factors and three levels, as shown in Table 1. These levels were designed after reviewing the results of Tabatabaei *et al.*[18] The review showed that a high proportion of methanol was required, depending on the kind of feedstock oil; moreover, the reaction temperature was higher than that of methanol reflux in a continuous system because the microwave-assisted conversion was performed in a closed batch system for a specified reaction time.

Normally, PFAD is a white-yellow soft wax at room temperature and takes the form of a clear liquid with light brown color at around 50 °C,[10] so before using PFAD, it was heated to 50 °C and mixed in the desired molar ratio with methanol (MeOH), and commercial sulfuric acid (H_2SO_4 at 98% concentration) was added to 2 wt% of the liquid mixture as an acid catalyst, so that the total volume of the liquid mixture was 1800 mL in every experimental run. The liquid mixture was then loaded into the Duran batch reactor, which was placed inside the microwave cavity to produce MWBD by esterification. The optimal operating point giving the maximum %FFA conversion at the minimum cost (USD) would be selected (by optimizing with the fitted models) to produce liquid MWBD and test it in a single-cylinder diesel engine.

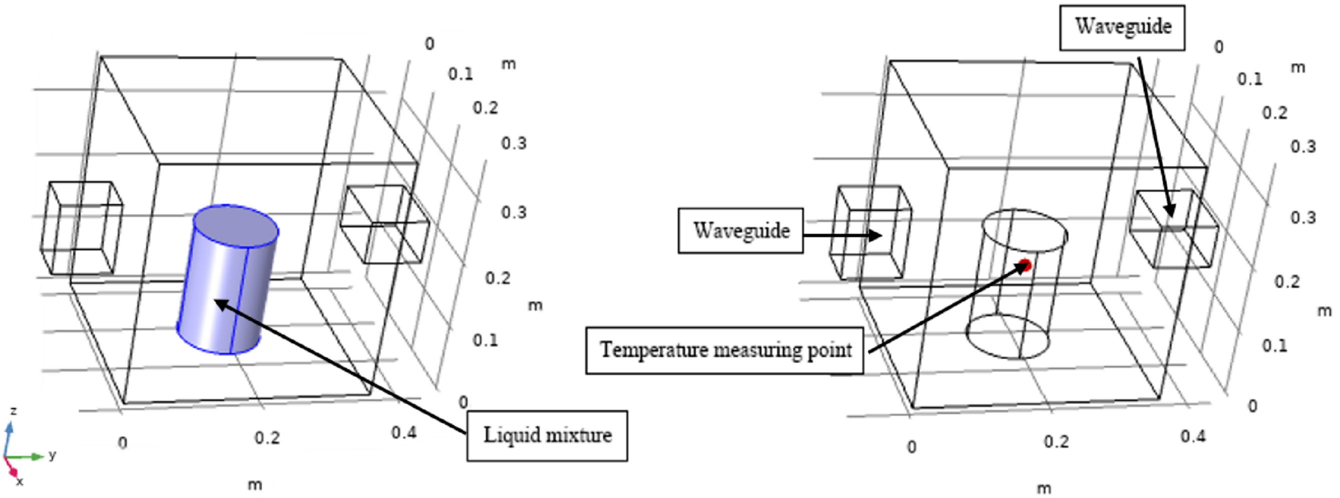
Simulation of the liquid mixture temperature profile

Multiphysics simulations were run to assess the period that the temperature steeply increases in the liquid mixture under microwave heating or called the temperature transient period the temperature transient in the liquid mixture under microwave heating, by using the COMSOL, Inc. (Burlington, MA 01803 USA) Multiphysics software package with the assumption that the air surrounding the reaction medium was constant; the liquid mixture in the transient period (60 s) consisted of PFAD and methanol only; and it remained a liquid during the esterification process. The sulfuric acid catalyst was omitted from this simulation, and the model ignored the chemical conversion reactions. Finally, the liquid mixture was in the laminar flow regime and was considered a homogenous single phase

Table 1. Factors and their levels in the experimental design of this study.

Factor	Unit	Level		
		−1	0	+1
Molar ratio (*R*); PFAD:Methanol	mol:mol	1:7	1:9	1:11
Temperature (*T*)	°C	70	80	90
Time (*t*)	min	20	30	40

Abbreviation: PFAD, palm fatty acid distillate.



(a) (b)

Figure 2. (a) Microwave-assisted biodiesel conversion model, and (b) temperature measuring point.

solution.[19] The time profile of the temperature in the liquid mixture was obtained by using a type-K thermocouple placed in the middle of the reactor, as shown in Fig. 2. The same location was probed in the model simulations for comparisons.

The governing equations of the current model consist of Maxwell's equations for electric field distribution, coupled with energy conservation of heat transfer in liquid mixture, and Navier–Stokes equations for mass and momentum conservation of the liquid assumed to have laminar flow conditions, as shown in Eqns (1)–(4):

$$\nabla \times \mu_r^{-1}\left(\nabla \times \vec{E}\right) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\epsilon_0}\right)\vec{E} = 0 \tag{1}$$

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \vec{u}\cdot\nabla T - \nabla\cdot\left(k\nabla T\right) = \omega\varepsilon_0\varepsilon_r''\left|E\right|^2 \tag{2}$$

$$\frac{\partial \rho}{\partial t} + \nabla\cdot\left(\rho\vec{u}\right) = 0 \tag{3}$$

$$\rho\frac{\partial \vec{u}}{\partial t} + \rho\vec{u}\cdot\nabla\vec{u} = -\nabla p + \left[\mu\left(\nabla\vec{u} + \left(\nabla\vec{u}\right)^T\right) - \frac{2}{3}\left(\mu\left(\nabla\cdot\vec{u}\right)\right)\right] - \rho\vec{g} \tag{4}$$

Here, μ_r is the relative permeability ($\mathrm{H\,m^{-1}}$), j is the imaginary unit, σ is the conductivity (S), ω is the angular frequency ($\mathrm{rad\,s^{-1}}$), ε_r is the relative permittivity, ε_0 is the permittivity of free space ($\mathrm{F\,m^{-1}}$), ρ is the fluid density ($\mathrm{kg\,m^{-3}}$), μ is the molecular viscosity coefficient, and $\vec{g}$ is the gravitational acceleration. The liquid mixture properties, which depend on the molar fraction ($x_i = c_i/c_{tot}$; concentration of species i, and total concentration) of each component, were calculated using the molar fractions as weights. The relative complex permittivity, the dynamic viscosity, thermal conductivity, specific heat capacity, and density of liquid mixture for a species i (PFAD and methanol) were therefore calculated as molar-weighted averages, as expressed in Eqns (5)–(10). The initial parameters and properties needed in this model are listed in Table 2.

$$\varepsilon = \varepsilon_0\sum_{i=1}^{2}\left(x_i\varepsilon_{r,i}\right) \tag{5}$$

$$\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'' \tag{6}$$

$$\mu = \sum_i x_i\mu_i \tag{7}$$

$$k = \sum_i x_i k_i \tag{8}$$

$$c_p = \sum_i x_i c_{pi} \tag{9}$$

$$\rho = \sum_i x_i \rho_i \tag{10}$$

A single-cylinder diesel engine test

Before starting the test, the MWBD was stirred and heated to evaporate moisture, at 110 °C for 60 min, and it was characterized for its biodiesel properties by the Office

Table 2. Summary of initial conditions and parameters applied in the model.

Parameter	Unit	PFAD	Methanol	Liquid mixture ratio		
				1:7	1:9	1:11
Complex relative permittivity (ε_r^*)	—	2.78–0.17*j*	26.39–10*j*	23.15–8.66*j*	23.76–8.92*j*	24.17–9.08*j*
Dynamic viscosity (*μ*)	mPa s	12.75	0.34	0.002	0.002	0.001
Thermal conductivity (*k*)	$\mathrm{W\,m^{-1}K^{-1}}$	0.17	0.20	0.19	0.19	0.20
Specific heat capacity (c_p)	$\mathrm{J\,kg^{-1}K^{-1}}$	2183	2520	2448	2459	2467
Density (ρ)	$\mathrm{kg\,m^{-3}}$	885.6	792	794	793	792

Abbreviation: PFAD, palm fatty acid distillate.

of Scientific Instrument and Testing, Prince of Songkla University, Hat-Yai Campus, Songkhla, Thailand. The results are shown in Tables 7 and 8. Then, three liquid fuels were prepared: a pure MWBD, a 50:50 blend of MWBD and a CHSD, named a liquid fuel blend (LFB), and a pure CHSD. The CHSD was purchased from the Bangchak fuel station in Prince of Songkla University Hat-Yai Campus. Since 2015, the Thai government has required CHSD to contain at least 6-7 vol% FAME for promoting energy security and national economy. However, its real composition was not analyzed in this study. The single-cylinder diesel engine Kubota model RT80 with specifications shown in Table 3[20] was tested on a 12 hp Plint & Partner dynamometer, with setup schematically shown in Fig. 3. The engine was tested at a constant 2200 rpm speed (ranging within ±10 rpm) with loads of 1.28, 2.56, 3.86, and 5.09 kW ± 0.5%, and with three replications per load. The actual load ranges tested were the same in terms of computed brake mean effective pressure for a speed of 2200 rpm ± 0.6%. The force delivered on dynamometer with a fixed inside arm length of 1.05 ft for the engine test was therefore used to calculate the brake torque and the corresponding brake power was measured using a spring balance, Salter (3.90–19.50 ± 0.05 lbf). The volumetric flow rate of fuel was measured using a scaling tube (50.0 ± 0.5 mL) coupled with a digital stopwatch, which had a resolution of 0.01 s, in the range 88.70–521.97 s ± 0.5%; moreover, the engine speed was measured using an increment encoder model PR-01N-S (resolution 0.1 rpm), and a type-K thermocouple (resolution 0.01 °C) was connected to the PC-based data logger, model AI210. It measured the fuel temperature (30.97–37.47 °C) and exhaust gas temperature (EGT: 140.74–465.44 °C ± 0.5%) and the accuracy of the measured quantities and the uncertainties of calculations are summarized in Table 4. The engine test system schematic is shown in Fig. 3.[21]

Table 3. Test engine specifications.

Engine type	Four-stroke compression ignition
Compression ratio	23:1
Number of cylinder	1
Cylinder arrangement	Horizontal
Bore/stroke	84 mm/84 mm
Displacement volume	465 cm^3
Method of charging	Naturally aspirated
Maximum power (new engine)	5.9 kW at 2400 rpm
Maximum torque (new engine)	2.8 kg m at 1600 rpm
Injection type	IDI-mechanically controlled
Injection pressure	140 $kg\,cm^{-2}$
Cooling type	Water

Abbreviation: DI, indirect injection.

Results and discussion

Optimizing microwave-assisted synthesis of biodiesel

Two responses, namely the maximum %FFA conversion and the minimum production cost (USD) were targeted by the experimental optimization using the Box–Behnken

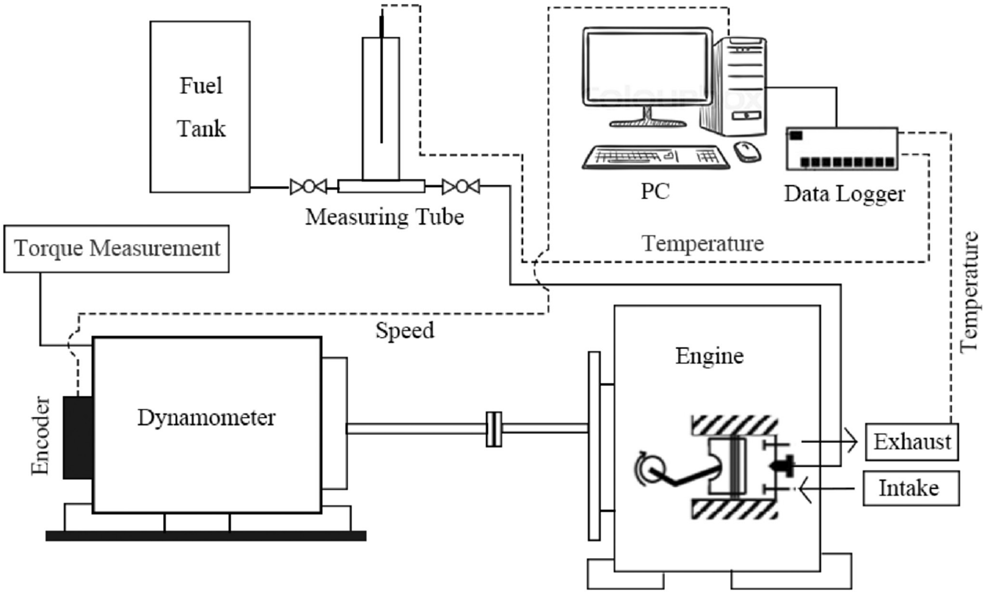


Figure 3. A schematic diagram of the engine test set-up.

Table 4. Measurement accuracies and uncertainties of the calculated results.

Measure quantity	Accuracy	Calculated quantity	Uncertainty (%)		
			1200 rpm	1700 rpm	2200 rpm
Force on dynamometer set	±0.05 lbf (±0.22 N)	Fuel volume and mass flow rates	±1.1	±1.1	±1.1
Engine torque	±0.05 lbf ft (±0.07 N m)	Brake power	±0.8	±0.6	±0.5
Engine speed	±10 rpm	Brake mean effective pressure (BMEP)	±1.2	±0.8	±0.6
Time for fuel flow rate	±0.5%	Brake specific fuel consumption (BSFC)	±1.4	±1.3	±1.2
Exhaust gas temperature (EGT)	±0.5%	Brake thermal efficiency (BTE)	±1.4	±1.3	±1.2

Abbreviations: BMEP, brake mean effective pressure; BSFC, brake specific fuel consumption; BTE, brake thermal efficiency; EGT, Exhaust gas temperature.

Table 5. Experimental Box–Behnken design and results of the FFA conversion (%) response in MW-assisted biodiesel production (currency conversion 33.51 baht/USD on April 1, 2022).

Run	Factors			FFA conversion (%)		Cost (USD)	
	Ratio (PFAD:MeOH)	Temperature (°C)	Time (min)	Experimental	Predicted	Experimental	Predicted
1	11	80	20	97.92	98.43	1.28	1.22
2	11	90	30	95.25	96.16	1.33	1.34
3	7	70	30	96.22	96.54	1.39	1.36
4	11	80	40	96.44	97.07	1.29	1.28
5	9	80	30	97.96	98.30	1.30	1.35
6	7	80	20	94.95	95.55	1.43	1.42
7	9	70	20	97.15	97.51	1.29	1.23
8	9	80	30	97.15	98.30	1.44	1.35
9	9	90	40	96.14	97.05	1.61	1.47
10	9	70	40	95.34	97.43	1.32	1.29
11	9	90	20	97.62	95.53	1.42	1.41
12	7	80	40	95.55	98.35	1.47	1.48
13	7	90	30	97.96	96.20	1.59	1.54
14	9	80	30	97.96	98.30	1.33	1.35
15	11	70	30	97.62	98.18	1.21	1.16

Abbreviations: FFA, free fatty acid; MeOH, methanol; PFAD, palm fatty acid distillate.

design, with the factors and their levels shown in Table 1. The %FFA conversion and cost responses, shown in Table 5, were obtained for 15 experimental runs. In the experimental results, first the temperature increased from the initial state to the setpoint temperature (70, 80, or 90 °C) during 2.47 ± 0.40, 3.26 ± 0.80, and 4.10 ± 1.08 min, respectively, while the average total power consumptions for producing MWBD fuel at these setpoints (70, 80, and 90 °C) were 0.21 ± 0.07, 0.26 ± 0.03, and 0.34 ± 0.07 kWh, respectively. The quadratic model fits to predict the %FFA conversion and the linear model fits to predict the cost, as shown in Eqns (11)–(12).

$$\begin{aligned}\mathit{FFA}\text{ conversion}\left(\%\right) = 2.040 + 5.833R + 1.610T + 0.436t \\ -0.021RT - 0.052Rt + 0.004Tt \\ -0.133R^2 - 0.010T^2 - 0.004t^2\end{aligned} \quad (11)$$

$$\text{Cost}\left(\mathit{USD}\right) = 0.972 - 0.048R + 0.009T + 0.003t \quad (12)$$

Here, R is the molar ratio of PFAD to methanol, T is the reaction temperature, and t is the reaction time. Analysis of variance of these regression models at the confidence level 95% ($\alpha = 0.05$) is shown in Table 6. The *P*-value was

Table 6. ANOVA for the response surface regression models of FFA conversion (%) and cost (USD).

Source	SS	df	MS	*F*-value	*P*-value
FFA conversion (%)					
Model	14.98	9	1.66	11.00	0.0083
Residual	0.7563	5	0.1513		
Lack of fit	0.3189	3	0.1063	0.4860	0.7262
Pure error	0.4374	2	0.2187		
Total	15.74	14			
Cost (USD)					
Model	0.1517	3	0.0506	17.75	0.0002
Residual	0.0313	11	0.0028		
Lack of fit	0.0205	9	0.0023	0.4184	0.8530
Pure error	0.0109	2	0.0054		
Total	0.1830	14			

Abbreviations: df, degrees of freedom; FFA, free fatty acid; MS, mean sum of squares; SS, sum of squares.

better than 0.05 for both regression models, which indicates the high significance of the models, while the coefficients of determination (R^2) and the adjusted coefficients of determination (R^2_{adj}) of %FFA conversion and cost (USD) were 0.9519, 0.8288, and 0.8654, 0.7821, respectively.

In the results, the time factor (t) was not significant, so the two-dimensional response surface contour plots of the two responses (%FFA conversion and cost) are shown in Fig. 4(a) and (b) only for the 20 min process duration. The optimal operating point is shown by the red point in this figure: ratio (PFAD:MeOH) 1:9, and temperature 80 °C. The correlation between the predicted results from regression models and the actual experimental results in Table 5 is plotted in Fig. 4(c), (d). The plots show straight trend lines with R^2 0.9519 and 0.8654 for %FFA conversion and cost (USD), respectively. The MWBD conversion was validation tested under these candidate optimal conditions, and the product performance was then tested by using the single-cylinder diesel engine.

Temperature profile of the liquid mixture

The initial time profiles of temperature from simulations that were described above in the section on the simulation of the liquid mixture temperature profile are shown with the experimental results in Fig. 5, for the various mixtures labeled by molar ratio (R). The temperature increased rapidly, and more so when the molar ratio of PFAD to methanol was increased. This is because the complex relative permittivity of the liquid mixture increased with the ratio PFAD:MeOH. This affects heating by microwaves via the dielectric mechanisms, dipolar polarization and ionic conduction, which strongly affect the relative dielectric loss factor. Other key factors are electric field strength and the temperature of the material.[22,23]

Fuel performance tested in a single-cylinder diesel engine

The properties of MWBD are summarized in Table 7. All the properties complied with Thai standards except for the DG and TG content, which exceeded the standard specifications. Biodiesel conversion in a two-stage process should therefore be tested, potentially to provide an improvement on this single-stage approach. The two-stage system is motivated by reducing operating costs, a lower alcohol ratio, reduced reaction time, and minimized yield losses.[24] The key properties of the three liquid fuels – a pure MWBD, a liquid fuel blend (LFB, MWBD:CHSD 50:50 by volume), and a pure CHSD – are summarized in Table 8. The cold flow properties, characterized by cloud and pour points, indicate the potential of a diesel fuel for various climates, and the three cases met the Thai agricultural engine diesel (AED) and high-speed diesel (HSD) standards. They are all appropriate for a warm climate like that in Thailand. Another important flow property is viscosity, which affects fuel injection, atomization, combustion behavior, and engine performance and emissions. However, the MWBD had a dramatically higher viscosity than CHSD (+59.9%), and it was slightly higher than the upper regulatory limit of Thai HSD standard (+22.4%), but still met the Thai AED standard. The properties indicating corrosive wear of diesel engine parts and fuel system are acid value and copper strip corrosion. The MWBD had a low titrated acid value, and its copper strip corrosion was in category No. 1a, meaning low corrosive wear, and it met both Thai AED and HSD standards. This is because the PFAD was mainly composed of weakly acidic tail oil monoacid, which does not cause high-rate corrosive wear.[21] Density relates to the mass of fuel injected to the cylinder. Normally, the density of biodiesel from PFAD is slightly higher than that of CHSD by +7.1% at 50 °C.[20] This was found also in this study. The densities of MWBD and LFB were higher than that of the CHSD by +5.8% and +1.8% at 15 °C, respectively, and met both Thai AED and HSD standards. Heating value stands for the direct energy content supplied to the engine. These values of MWBD and LFB were lower than that of the CHSD by −21.5% and −10.7%, respectively. A previous study[20] also found that biodiesel from PFAD had a slightly lower heating value than CHSD, by −12.8%. The last important property is the flash point, which relates to safe storage and utilization of the diesel fuel. It is the lowest temperature that will allow ignition when injected to an ignition source. The

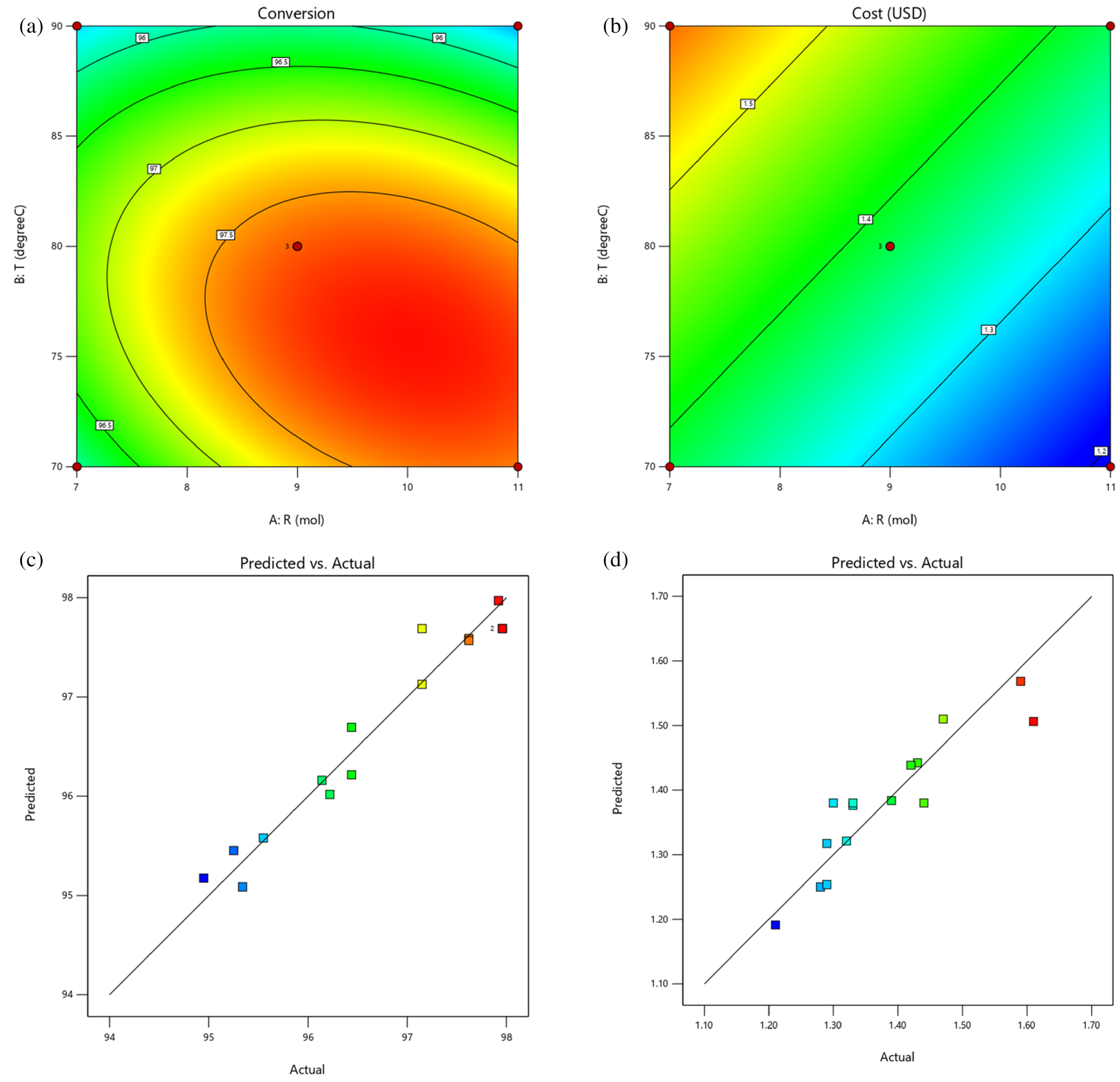


Figure 4. Two-dimensional response surface contour plots with blend ratio and temperature axes are shown in the top panels (a) and (b), and the correlation plots of actual (experimental) and model fit are shown in the bottom panels (c) and (d) for %FFA conversion and cost (USD).

MWBD met both Thai AED and HSD standards for flash point, and it can be considered safe for use as a diesel fuel.

The most important engine performance results, the average brake specific fuel consumption (BSFC) and the average brake thermal efficiency (BTE), are shown in Fig. 6, in the top and the bottom panels, respectively. The BSFC reflects the combustion engine's efficiency in producing mechanical power, and on the other hand, the BTE is a fundamental quantity (unitless bare number). Normally, these are considered indexes for comparison with a theoretical value. The BSFC with various loads at the fixed rotation speed at 2200 rpm can be seen in the top panel of Fig. 6. The BSFCs of MWBD and LFB were generally higher than that of CHSD over almost all of the conditions tested; moreover, the BSFC increased slightly with the proportion of MWBD. Similar results have been reported for various

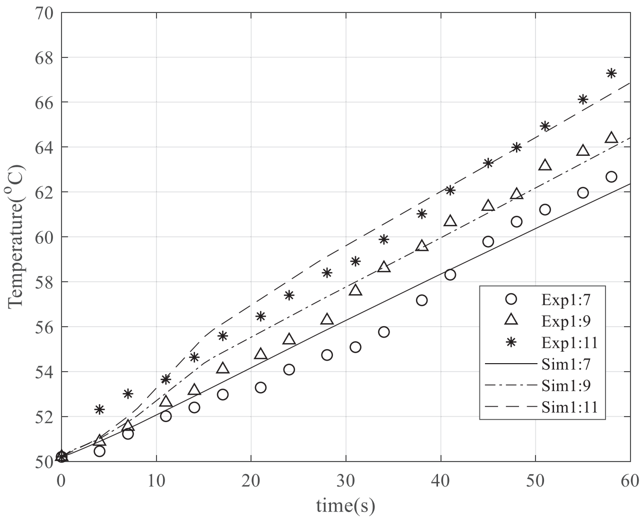


Figure 5. Temperature profile vesus time for simulations (Sim) and experiments (Exp).

Table 7. Properties of MWBD.

Property	Test method	Thai standards	MWBD
Water content (wt%)	Karl fisher	<0.05	0.04
Oxidation stability at 110 °C	EN 15751	> 10	>24
Linolenic acid methyl ester (wt%)	EN 14103	<12	0.296
Methanol (wt%)	EN 14130	<0.20	0.11
Methyl ester (wt%)	EN 14103	<96.5	90.15
Monoglyceride (wt%)	EN 14105	<0.70	0.28
Diglyceride (wt%)		<0.20	1.58
Triglyceride (wt%)			2.8

Abbreviation: MWBD, microwave- assisted biodiesel.

diesohols, because the liquid fuel blend generally has slightly lower heating value than CHSD.[25–30] The results in terms of energy efficiency are seen in the bottom panel of Fig. 6. The BTEs of MWBD and LFB were higher than that of CHSD in all conditions tested, and the improvement gap in BTE increased at high operating loads. The BTEs seen for various liquid fuel blends (like anhydrous *n*-butanol-based diesohol) were also better than that for diesel in previous studies.[31–33]

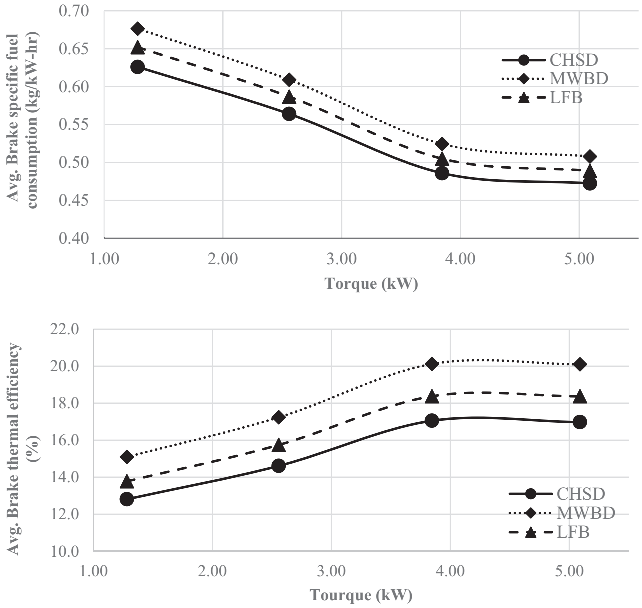


Figure 6. Engine performance at different loads. Average break specific fuel consumption (BSFC) in the top panel and average brake thermal efficiency (BTE%) in the bottom panel.

Conclusions

The MWBD conversion of PFAD by esterification was performed in a batch reactor with two microwave sources (magnetrons). The experiments for response surface modeling followed a Box–Behnken design. The optimal conditions giving maximum %FFA conversion at a minimum cost (USD) had molar ratio (PFAD:methanol) 1:9, temperature 80 °C, and duration 20 min. The regression models that forecast %FFA conversion and cost (USD) fit the experimental results with coefficients of determination (R^2) at 0.9519 and 0.8654, respectively. The time profiles of the temperature at the center of the reactor were simulated with the FEM, using molar-averaged material properties, and they matched the experimental results well. The MWBD conversion under the model-predicted optimal conditions was tested, and the resulting fuel was blended with CHSD 50:50 by volume (liquid fuel blended = LFB). The most important fuel properties of MWBD, LFB, and CHSD met both Thai AED and HSD standards. All these liquid fuels performed well when tested in a single-cylinder diesel engine, being similar to each other in performance and not causing any problems.

Acknowledgements

This work was supported by the Thai government (grant no. SIT6205123S, 2019), and the authors thank the research and development office (RDO) of Prince of Songkla University,

Table 8. Important properties of liquid fuels.

Property		Fuel		Test method	Thai standards of AED/HSD
	MWBD	LFB	CHSD[21]		
Cloud point (°C)	13	—	8	ASTM D2500	n.a./n.a.
Pour point (°C)	10	—	– 5	ASTM D97	n.a./<10
Kinematic viscosity at 40 °C (mm^2 s^{-1})	5.02	—	3.14	ASTM D445	1.9–8.0/1.8–4.1
Acid value (mgKOH g^{-1})	0.055	—	0.05	ASTM D664	≤0.80/n.a
Copper strip corrosion (no.)	1a	—	1a	ASTM D130	≤3/<1
Density at 15 °C (kg dm^{-3})	879.9	846.95	832	ASTM D1298	860–900/810–870
Density at 30 °C (kg dm^{-3})	869.17	836.62	821.85		n.a./n.a.
Higher heating value (kJ kg^{-1})	35 262	40 081	44 900	ASDT D240	n.a./n.a.
Flash point (°C)	137	—	69	ASTM D93	≥120/>52

AED, agricultural engine diesel; CHSD, commercial high-speed diesel; HSD, high speed diesel; LFB, liquid fuel blend; MWBD, microwave-assisted biodiesel; n.a., not available.

Hat-Yai Campus, and Prince of Songkla University, Surat-Thani Campus for supporting this project under the Integrated High Value of Oleochemical (IH-VO) Research Center. Mrs Enarm Promnonsri thanks the Interdisciplinary Graduate School of Energy System (IGS-Energy), Prince of Songkla University for supporting scholarships.

References

1. Eguchi S, Kagawa S and Okamoto S, Environmental and economic performance of a biodiesel plant using waste cooking oil. *J Clean Prod* **101**:245–250 (2015). https://doi.org/10.1016/j.jclepro.2015.04.008.
2. Abdul Kapor NZ, Maniam GP, Rahim MHA and Yusoff M, Palm fatty acid distillate as a potential source for biodiesel production – A review. *J Clean Prod* **143**:1–9 (2017). https://doi.org/10.1016/j.jclepro.2016.12.163.
3. Khodadadi MR, Malpartida I, Tsang C-W, Lin CSK and Len C, Recent advances on the catalytic conversion of waste cooking oil. *Mol Catal* **494**:111128 (2020). https://doi.org/10.1016/j.mcat.2020.111128.
4. Costa AFD, De Oliveira ADN, Esposito R, Len C, Luque R, Noronha RCR *et al.*, Glycerol and catalysis by waste/low-cost materials– A review. *Catalysts* **12**(5):570 (2022).
5. Su T, Zhao D, Khodadadi M and Len C, Lignocellulosic biomass for bioethanol: recent advances, technology trends, and barriers to industrial development. *Curr Opin Green Sustain Chem* **24**:56–60 (2020). https://doi.org/10.1016/j.cogsc.2020.04.005.
6. Sangar SK, Syazwani ON, Farabi MSA, Razali SM, Shobhana G, Teo SH *et al.*, Effective biodiesel synthesis from palm fatty acid distillate (PFAD) using carbon-based solid acid catalyst derived glycerol. *Renew Energy* **142**:658–667 (2019). https://doi.org/10.1016/j.renene.2019.04.118.
7. Feyzi M, Hassankhani A and Rafiee HR, Preparation and characterization of Cs/Al/Fe3O4 nanocatalysts for biodiesel production. *Energ Conver Manage* **71**:62–68 (2013). https://doi.org/10.1016/j.enconman.2013.03.022.
8. Gupta AR and Rathod VK, Solar radiation as a renewable energy source for the biodiesel production by esterification of palm fatty acid distillate. *Energy* **182**:795–801 (2019). https://doi.org/10.1016/j.energy.2019.05.189.
9. Natthapon S and Krit S, Optimization of methyl ester production from palm fatty acid distillate using single-step esterification: A response surface methodology approach. *ARPN J Eng Appl Sci* **10**(16):7075–7079 (2015).
10. Metre A and Nath K, Process optimization of super phosphoric acid-catalyzed esterification of palm fatty acid distillate using response surface methodology. *Biomass Convers Biorefin* **5**(4):397–407 (2015). https://doi.org/10.1007/s13399-014-0157-z.
11. Kanjaikaew U, Tongurai C, Chongkhong S and Prasertsit K, Two-step esterification of palm fatty acid distillate in ethyl ester production: Optimization and sensitivity analysis. *Renew Energy* **119**:336–344 (2018). https://doi.org/10.1016/j.renene.2017.12.002.
12. Gude VG, *Micorwave-Mediated Biofuel Production*. CRC PRESS, Taylor & Francis Group, Boca Raton, FL, pp. 28–61 (2017).
13. Athar M, Imdad S, Zaidi S, Yusuf M, Kamyab H, Jaromír Klemeš J *et al.*, Biodiesel production by single-step acid-catalysed transesterification of Jatropha oil under microwave heating with modelling and optimisation using response surface methodology. *Fuel* **322**:124205 (2022). https://doi.org/10.1016/j.fuel.2022.124205.
14. Pham EC, Le TVT, Le KCT, Ly H, Vo BNT, Van Nguyen D *et al.*, Optimization of microwave-assisted biodiesel production from waste catfish using response surface methodology. *Energy Rep* **8**:5739–5752 (2022). https://doi.org/10.1016/j.egyr.2022.04.036.
15. Jeni K, Yapa M and Rattanadecho P, Design and analysis of the commercialized drier processing using a combined unsymmetrical double-feed microwave and vacuum system (case study: Tea leaves). *Chem Eng Process* **49**(4):389–395 (2010). https://doi.org/10.1016/j.cep.2010.03.003.

16. Jindarat W, Rattanadecho P, Vongpradubchai S and Pianroj Y, Analysis of energy consumption in drying process of non-hygroscopic porous packed bed using a combined multi-feed microwave-convective air and Continuous Belt system (CMCB). *Drying Technol* **29**(8):926–938 (2011). https://doi.org/10.1080/07373937.2011.560318.
17. Pianroj Y, Jumrat S, Werapun W, Karrila S and Tongurai C, Scaled-up reactor for microwave induced pyrolysis of oil palm shell. *Chem Eng Process* **106**:42–49 (2016). https://doi.org/10.1016/j.cep.2016.05.003.
18. Tabatabaei M, Aghbashlo M, Dehhaghi M, Panahi HKS, Mollahosseini A, Hosseini M *et al*., Reactor technologies for biodiesel production and processing: A review. *Prog Energy Combust Sci* **74**:239–303 (2019). https://doi.org/10.1016/j.pecs.2019.06.001.
19. Selemani A, Thermal chemical enhancement and influence of fluid flow in transesterification of palm oil. *Energy Sources Part A Recovery Util Environ Eff* **40**(1):81–87 (2018). https://doi.org/10.1080/15567036.2017.1405113.
20. Eiadtrong S, Maliwan K, Prateepchaikul G, Kattiyawan T, Thephsorn P and Leevijit T, Preparation, important fuel properties, and comparative use of un-preheated palm fatty acid distillate-diesel blends in a single cylinder diesel engine. *Renew Energy* **134**:1089–1098 (2019). https://doi.org/10.1016/j.renene.2018.09.043.
21. Eiadtrong S, Maliwan K, Theppaya T, Kattiyawan T, Prateepchaikul G and Leevijit T, An investigation to utilize ternary diesel-palm fatty acid distillate-10 wt% n-butanol blends as simply novel diesel substitutes. *Fuel* **289**:119965 (2021). https://doi.org/10.1016/j.fuel.2020.119965.
22. Sun J, Wang W and Yue Q, Review on microwave-matter interaction fundamentals and efficient microwave-associated heating strategies. *Materials* **9**(4):1–25 (2016). https://doi.org/10.3390/ma9040231.
23. Rosa R, Veronesi P and Leonelli C, A review on combustion synthesis intensification by means of microwave energy. *Chem Eng Process* **71**:2–18 (2013). https://doi.org/10.1016/j.cep.2013.02.007.
24. Thoai DN, Tongurai C, Prasertsit K and Kumar A, Review on biodiesel production by two-step catalytic conversion. *Biocatal Agric Biotechnol* **18**:101023 (2019). https://doi.org/10.1016/j.bcab.2019.101023.
25. Atmanli A, Ileri E, Yuksel B and Yilmaz N, Extensive analyses of diesel–vegetable oil–n-butanol ternary blends in a diesel engine. *Appl Energy* **145**:155–162 (2015). https://doi.org/10.1016/j.apenergy.2015.01.071.
26. Atmanlı A, İleri E and Yüksel B, Experimental investigation of engine performance and exhaust emissions of a diesel engine fueled with diesel – n-butanol–vegetable oil blends. *Energ Conver Manage* **81**:312–321 (2014). https://doi.org/10.1016/j.enconman.2014.02.049.
27. Rakopoulos DC, Rakopoulos CD, Giakoumis EG, Dimaratos AM and Kyritsis DC, Effects of butanol–diesel fuel blends on the performance and emissions of a high-speed DI diesel engine. *Energ Conver Manage* **51**(10):1989–1997 (2010). https://doi.org/10.1016/j.enconman.2010.02.032.
28. Atmanli A, Comparative analyses of diesel–waste oil biodiesel and propanol, n-butanol or 1-pentanol blends in a diesel engine. *Fuel* **176**:209–215 (2016). https://doi.org/10.1016/j.fuel.2016.02.076.
29. Damodharan D, Sathiyagnanam AP, Rana D, Rajesh Kumar B and Saravanan S, Extraction and characterization of waste plastic oil (WPO) with the effect of n-butanol addition on the performance and emissions of a DI diesel engine fueled with WPO/diesel blends. *Energy Convers Manag* **131**:117–126 (2017). https://doi.org/10.1016/j.enconman.2016.10.076.
30. Alptekin E, Emission, injection and combustion characteristics of biodiesel and oxygenated fuel blends in a common rail diesel engine. *Energy* **119**:44–52 (2017). https://doi.org/10.1016/j.energy.2016.12.069.
31. Atmanli A, Ileri E and Yilmaz N, Optimization of diesel–butanol–vegetable oil blend ratios based on engine operating parameters. *Energy* **96**:569–580 (2016). https://doi.org/10.1016/j.energy.2015.12.091.
32. Chen Z, Liu J, Han Z, Du B, Liu Y and Lee C, Study on performance and emissions of a passenger-car diesel engine fueled with butanol–diesel blends. *Energy* **55**:638–646 (2013). https://doi.org/10.1016/j.energy.2013.03.054.
33. Rakopoulos DC, Rakopoulos CD, Papagiannakis RG and Kyritsis DC, Combustion heat release analysis of ethanol or n-butanol diesel fuel blends in heavy-duty DI diesel engine. *Fuel* **90**(5):1855–1867 (2011). https://doi.org/10.1016/j.fuel.2010.12.003.

Enarm Promnonsri

Enarm Promnonsri is a master's degree student majoring in energy technology in the Faculty of Engineering, Prince of Songkhla University, Hat-Yai Campus, Thailand.

Yutthapong Pianroj

Yutthapong Pianroj is an assistant professor at Prince of Songkla University, Suratthani Campus. He has various interests in both academic and industrial research, including applied physics, mathematical simulation, chemistry, and engineering. He has a PhD in energy technology.

Teerasak Punvichai

Teerasak Punvichai has a PhD in chemical/process engineering and is an associate professor in the Food Science and Technology Department, Prince of Songkla University. He works in food science and technology, agro-industry technology, chemical engineering, and fat and oil technology.

Seppo Karrila

Seppo Karrila has a PhD in chemical engineering and has been involved with a wide range of topics in both academic and industrial research, including chemistry, physics, mathematics, engineering, and bioinformatics. He currently serves as an associate professor at the Prince of Songkhla University, Thailand.

Sopida Sungsoontorn

Sopida Sungsoontorn has a PhD in mechanical engineering from Thammasat University, and is currently a lecturer and a researcher in the Department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Rattanakosin, Thailand. Her research interests include heat and mass transfer, drying, multi-phase flows in porous media, and microwave and dielectric material interactions.

Theerayut Leevijit

Theerayut Leevijit has a PhD in energy technology and has been involved with a wide range of research topics including energy technology, chemistry, and engineering. He currently serves as an associate professor at the Prince of Songkhla University, Thailand.

Saysunee Jumrat

Saysunee Jumrat has a PhD in civil engineering from Thammasat University. She is an assistance professor specializing in environmental sustainability in the Faculty of Science and Industrial Technology, Prince of Songkla University Suratthani Campus, Thailand. She has been involved in research on waste utilization for energy and composite materials.

VITAE

Name Miss Enarm Promnonsri

Student ID 6310120034

Educational Attainment

Degree	**Name of Institution**	**Year of Graduation**
Bachelor of Science (Engineering Management)	Prince of Songkla University	2019

Scholarship Awards during Enrolment

The National Research Council of Thailand under the Research University Network (RUN) project of the year 2020 and the 2022 Interdisciplinary Graduate School of Energy Systems (IGS-Energy) scholarships at the master's degree, Faculty of Engineering, Prince of Songkla University.