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Theme:

**THE INFLUENCE OF CATALYSTS ON THE TRANSESTERIFICATION
REACTION OF WASTE OILS FOR THE PRODUCTION OF BIOFUEL**

defended on: 06/06/2024

In front of a jury composed of:

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Dedication

I dedicate this thesis in particular to:

My dear parents, siblings and my loved people, you are and will remain the light that illuminates my path.

My friends Imane, Kaouther, Rania and Ranime, you have always encouraged me and that is a pleasure for me.

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Table of Contents

Table of Contents

DEDICATION	I
ACKNOWLEDGEMENTS	II
TABLE OF CONTENTS.....	III
LIST OF FIGURES	VI
LIST OF TABLES.....	VII
LIST OF ABBREVIATIONS	VIII
GENERAL INTRODUCTION.....	IX

CHAPTER 01: OVERVIEW ON THE PRODUCTION OF BIODIESEL

1.1 INTRODUCTION.....	1
1.2 DESCRIPTION OF THE TRANSESTERIFICATION REACTION.....	2
1.3 CATALYSTS	3
1.3.1 Alkaline catalysts.....	3
1.3.2 Acid catalysts.....	3
1.3.3 Enzymatic catalysts	3
1.3.4 Solid catalysts (Heterogeneous catalysis).....	4
1.4 PREPARATION OF BIODIESEL	4
1.4.1 Reaction mechanism	4
1.4.2 The separation and purification	5
1.4.3 Glycerol neutralization	5
1.5 TRANSESTERIFICATION REAGENTS	5
1.5.1 Triglycerides	6
1.5.2 Methyl or ethyl esters of biodiesel.....	6
1.6 TYPES OF CATALYSTS	6
1.6.1 Sodium hydroxide (KOH)	7
1.6.2 Sulphuric acid (H ₂ SO ₄).....	7
1.6.3 Enzymatic catalyst (lipase).....	8
1.7 EXPERIMENTAL CONDITIONS.....	8
1.7.1 Reaction temperature	9
1.7.2 Reaction time	9
1.8 BIODIESEL CHARACTERISTICS	9
1.8.1 Chemical structure	9
1.8.2 Viscosity	10
1.8.3 Cloud point	10
1.8.4 Flash point	10
1.8.5 Cetane index	10
1.8.6 Calorific value	11

1.8.7 Molar ratio oil/alcohol	11
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CHAPTER 02: EXPERIMENTAL PART

2.1 MATERIALS AND PRODUCTS	13
2.1.1 Equipment.....	13
2.1.2 Products	13
2.2 THE SAMPLING	13
Calculation of the approximate molar mass of Elio® oil	14
Calculation the mass of methanol	14
Calculation of the mass of KOH.....	14
Calculation of the volume of H ₂ SO ₄	15
Calculation of the mass of lipase	15
2.3 OPERATIONAL PROCESS	15
2.3.1 Reactants mixture	15
2.3.2 The reaction	15
2.3.3 Decanting.....	16
2.3.4 The wash and purification.....	16
2.4 TYPE OF CATALYST USED	16
2.4.1 Basic catalyst	16
2.4.2 Acid catalyst	17
2.4.3 Enzymatic catalyst.....	17
2.5 PHYSIC-CHEMICAL PROPERTIES	17
2.5.1 Viscosity test.....	17
2.5.2 Calorific value	18
2.5.3 Flash point	18
2.5.4 Infrared spectrum.....	19
2.5.5 Cloud point	19
2.5.6 Cetane index	20

CHAPTER 03: RESULTS AND DISCUSSION

3.1 ANALYSIS RESULTS OF BASIC CATALYST	22
3.1.1 Viscosity	22
3.1.2 Cloud point	22
3.1.3 Flash point	22
3.1.4 Cetane index	22
3.1.5 Calorific value	23
3.1.6 IR spectrum.....	23
3.2 ANALYSIS RESULTS OF ACID CATALYST.....	25
3.2.1 Viscosity	25
3.2.2 Cloud point	25
3.2.3 Flash point	25

3.2.4 Cetane index	25
3.2.5 Calorific value	26
3.2.6 IR spectrum.....	26
3.3 ANALYSIS RESULTS OF ENZYMATIC CATALYST	28
3.3.1 Viscosity	28
3.3.2 Cloud point	28
3.3.3 Flash point	28
3.3.4 Cetane index	28
3.3.5 Calorific value	29
3.3.6 IR spectrum.....	29
3.4 PHYSICOCHEMICAL PROPERTIES OF BIODIESEL.....	30
3.4.1 Viscosity	31
3.4.2 Cloud point	31
3.4.3 Flash point	31
3.4.4 Cetane index	32
3.4.5 Calorific value	32
3.5 YIELD CALCULATION	32
GENERAL CONCLUSION.....	33
BIBLIOGRAPHIC REFERENCES.....	35

List of figures

Figure 1: Biofuel Vs fossil fuel.

Figure 2: Organogram of biofuel generation.

Figure 3: Mechanism of transesterification process.

Figure 4: The catalytic mechanism of the transesterification reaction.

Figure 5: Scheme of the experimental apparatus for the transesterification reaction process.

Figure 6: Preparation steps of the biodiesel production.

Figure 7: Chemical structure of Mono-, Di- and Tri-Glycerides.

Figure 8: Reaction mechanism of triglycerides.

Figure 9: Mechanism of the transesterification reaction with KOH.

Figure 10: Mechanism of the transesterification reaction with H₂SO₄.

Figure 11: Commercialized Elio® oil and its composition.

Figure 12: Reactants of transesterification reaction.

Figure 13: Transesterification reaction process.

Figure 14: Decantation process.

Figure 15: The reaction products.

Figure 16: Viscometer (Herzog HVM 472).

Figure 17: Calorimeter (IKA C200).

Figure 18: ASTM D93 Pensky-Martens Closed Cup.

Figure 19: IR spectrophotometer (Cary 660 FT-IR).

Figure 20: Cloud Point Analyzer (ASTM D2500, D5771).

Figure 21: Fully-Automatic Cetane index Tester.

Figure 22: IR spectra of biodiesel for the KOH catalyst.

Figure 23: IR spectra of biodiesel for the H₂SO₄ catalyst.

Figure 24: IR spectra of biodiesel for the lipase catalyst.

List of tables

Table 1: Functional groups of biodiesel IR spectrum for KOH catalyst.

Table 2: Functional groups of biodiesel IR spectrum for H₂SO₄ catalyst.

Table 3: Functional groups of biodiesel IR spectrum for lipase catalyst.

Table 4: Biodiesel properties with different catalysts.

List of Abbreviations

ANP: The National Agency for Petroleum Natural Gas and Biofuels

ASTM D6751: US Biodiesel Blend Stock Standard

CI : cetane number

CP: cloud point

CV : calorific value

DG: diglycerides

EN14214: The European Biodiesel Standard

FAEE: fatty acid ethyl ester

FAME: fatty acid methyl ester

FFA: Free fatty acids

FP: flash point

g: Gramme

GHG: greenhouse gas

H₂SO₄: sulphuric acid

HCL: hydrogen chloride

IR: The infrared

KBr: Potassium bromide

KOH: potassium hydroxide

MG: monoglycerides

ml : milli litre

mm²/s : milli mètre carré par seconde.

NaCl: Sodium chloride

NaOH: sodium hydroxide

TG: triglycerides

WCO: waste cooking oil

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Currently, the transport sector relies mainly on liquid fuels because of their ability to be stored easily. The use of gaseous fuels in transport is relatively limited, and solid fuels have been used in the past for trains. Fossil fuels have a significant negative impact on the environment due to their intensive use. The combustion of oil derivatives is the main cause of greenhouse gas (GHG) emissions, particularly CO₂. It is essential to reduce fossil fuel consumption and explore various alternative energy sources. Biodiesel appears to be an appropriate alternative energy option.

Biodiesel has an important place in renewable energy sources due to its non-toxic nature, biodegradability, high calorific value (CV) and low Sulphur content. The use of biodiesel reduces unburnt and sooty emissions, while its compatibility with diesel engines allows seamless integration without the need for modifications. However, the main difficulty in producing and marketing biodiesel is the cost of production, which is primarily dependent on the raw material, other reagents and the type of process used. The yield of biodiesel also relates to the quality of the feedstock processed, as we will endeavor to show in this work.

The transesterification reaction is considered as one of the most important methods of processing vegetable oils into biodiesel because of the low cost and simplicity of the production process. This process transforms triglycerides in the presence of an alcohol (usually methanol or ethanol) and a catalyst into methyl or ethyl esters, producing glycerol as a by-product.

The objective of this research is to upgrade a used oil and compare the influence of each catalyst on biodiesel production with fixed parameters such as reaction temperature, oil/alcohol molar ratio, and reaction time. In our study, we used Elio oil, which is 100% soya oil, methanol as the alcohol and KOH, H₂SO₄ and lipase as the catalysts. The biodiesel obtained in the three tests will be characterized and the different results will be compared with biodiesels that correspond to international quality standards.

This dissertation was divided in three main chapters, in the first chapter we presented an overview about the production of biodiesel followed by a short description of the transesterification reaction. Also, the first chapter presents an informations about the main three catalysts used in this dissertation to produce biodiesel. The second chapter details the experimental methods and the different apparatus used to prepare the catalysts and biocatalyst using lipase enzyme and also describe the physical -chemical process. The third chapter presents the results obtained and the comparative study as well as the discussion about the analysis of the different samples of biodiesel obtained by using catalyst. Finally, a general conclusion resumes the finding of this work.

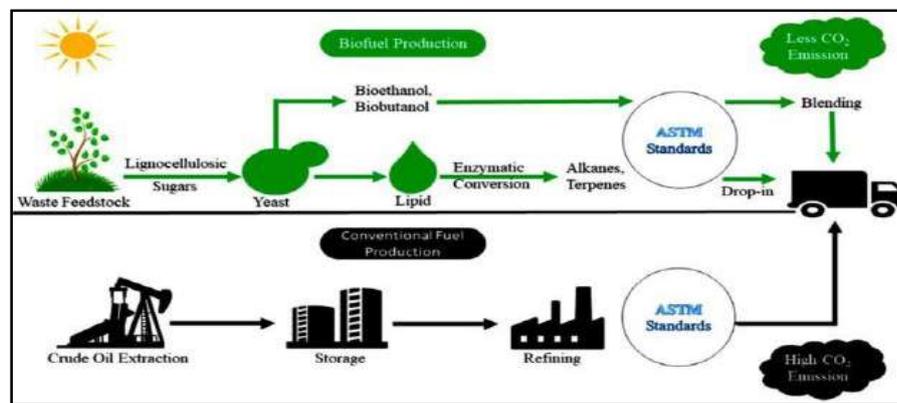
CHAPTER 01

OVERVIEW ON THE PRODUCTION OF BIODIESEL

1.1 Introduction

Biofuel is produced from renewable organic substances, such as plants, agricultural waste, animal fats or algae. These fuel sources are generally considered to be more environmentally friendly than fossil fuels, as they can be regenerated relatively quickly and, in some cases, can reduce the emission of greenhouse gases when used (Jeswani, Chilvers, et Azapagic 2020).

The National Agency for Petroleum Natural Gas and Biofuels (ANP) defines biodiesel as a fuel composed of alkyl esters of long carboxylic acids chains that is produced from the transesterification or esterification of fatty materials of vegetable or animal origin. Biodiesel can be used in internal combustion motors, gas turbines or similar power systems, and are often mixed with conventional fuels to reduce the need for fossil fuels and minimize the environmental impacts associated with their use (Dos Santos et al. 2020).



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Figure 1: Biofuel Vs fossil fuel.

There are three generations of biofuels, depending on the origin of the biomass used and the associated converting processes:

* First-generation of biofuel: First-generation biofuels are the most established type made from crops that are commonly used, these crops are processed for ethanol (from sugar cane, maize, sugar beet, wheat, etc.) by fermentation, and for biodiesel (from soya, rapeseed, palm oil, etc.) by transesterification. ((Étude de l'effet de la nature du catalyseur hétérogène dérivé de la biomasse Saharienne sur le rendement de la transestérification. (« History of Biofuels », s. d.)

* Second-generation of biofuel: Second-generation biofuels use non-food biomass sources. These include wood waste, agricultural wastes such as straw and corn stalks, and specific energy crops such as switch grass. The conversion process for second-generation biofuels uses

thermochemical techniques such as gasification or fast pyrolysis to break down complex cellulosic material into usable liquid fuels.

* Third-generation of biofuel: Third-generation biofuels are associated with algal biomass. Algae are a promising alternative to biomass because they reproduce rapidly and remove large quantities of CO₂ from the atmosphere. Although they are not very energy dense, which makes the current processing of algae-based biofuels inefficient.

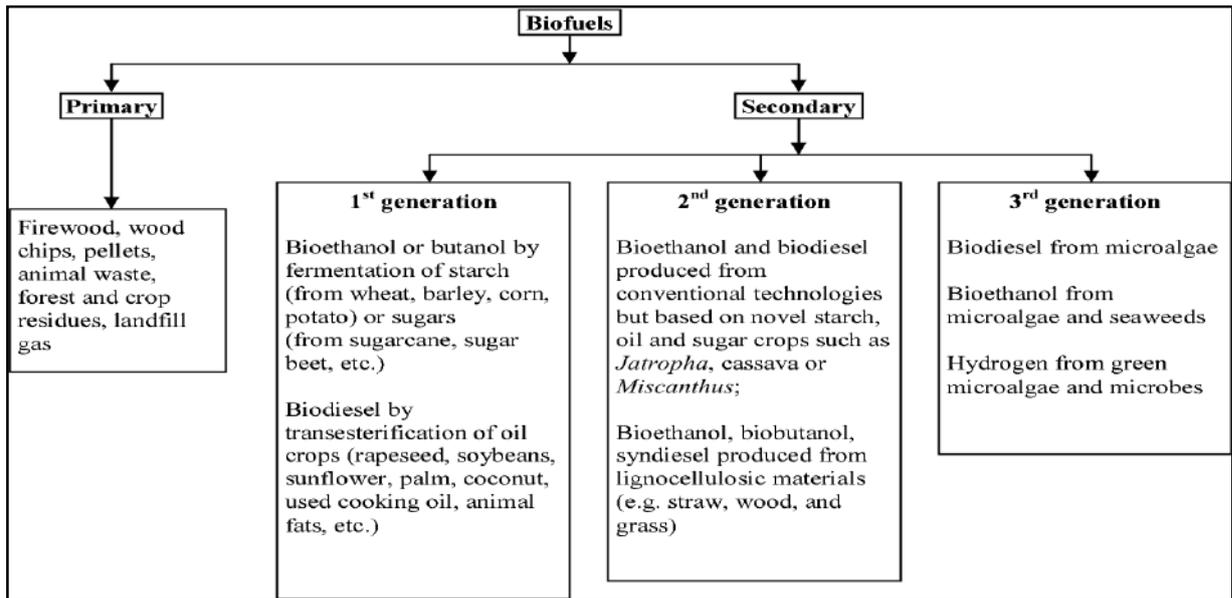


Figure 2: Organogram of biofuel generation.

1.2 Description of the transesterification reaction

The trans-esterification reaction is a key step in the production of biofuel from renewable sources, in which a vegetable oil or animal fat reacts with an alcohol in the presence of a catalyst to obtain a fatty acid ester (such as fatty acid methyl ester (FAME) or fatty acid ethyl ester (FAEE)) and glycerol), This reaction transforms these raw materials into a fuel that can be used in diesel motors, offering a more sustainable alternative to fossil fuels.

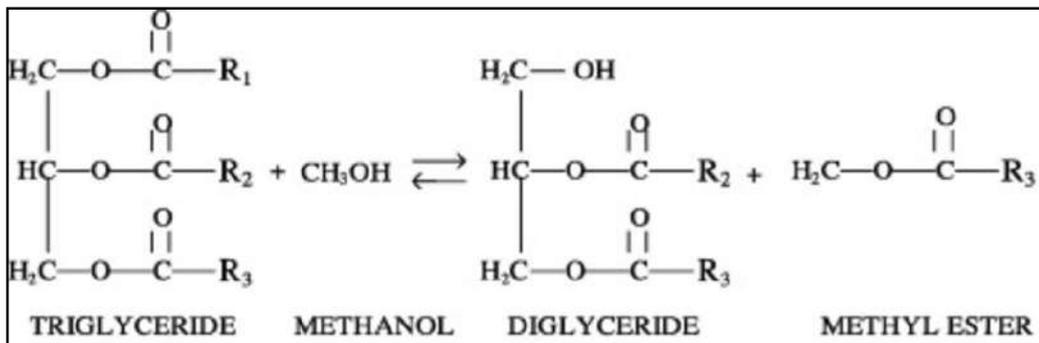


Figure 3: Mechanism of transesterification process.

The transesterification reaction consists of three successive steps:

The alcohols used in the transesterification reaction act as surfactants because they are soluble in glycerol (polar phase) and in biodiesel (non-polar phase). The carbon chain of the alcohol molecule is responsible for its solubility in biodiesel, whereas the hydroxyl group exhibits affinity for the glycerol.

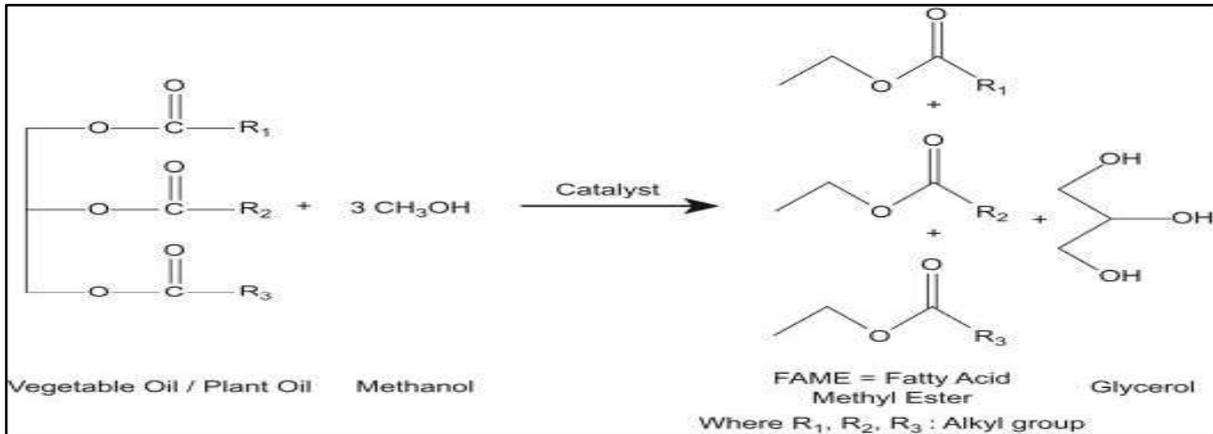


Figure 4: The catalytic mechanism of the transesterification reaction.

This process involves exchanging the organic group R'' of an ester with the organic group R' of an alcohol.

1.3 Catalysts

A catalyst is a substance that increases the speed of a chemical reaction without being consumed; it works by lowering the activation energy required for the reaction and improving its yield.

1.3.1 Alkaline catalysts

Alkaline catalysts such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) play an important role in promoting the transesterification reaction, because of their capacity to achieve high yields under relatively mild reaction conditions (Chizoo 2022).

1.3.2 Acid catalysts

Acid catalysts such as sulphuric, sulphonic and hydrochloric acids can also be used to catalyse the transesterification reaction. While acid catalysts offer a high level of efficiency, however the reaction rate is slower than that of alkaline catalysts (Lotero et al. 2005).

1.3.3 Enzymatic catalysts

Enzymatic catalysts, in particular lipases, are used in the transesterification reaction for biodiesel production because of their high efficiency, environmental benefits and ability to process oils with a high free fatty acid content (Amini et al. 2017).

1.3.4 Solid catalysts (Heterogeneous catalysis)

Solid catalysts can replace strong acids or bases in the transesterification reaction, which avoids the corrosion problems associated to chemical equipment and the environmental risks caused by liquid acids and bases (Malewska, Polaczek, et Kurańska 2022).

The choice of catalyst often depends on a number of factors, including the raw material source, reaction conditions, process simplicity, costs and environmental considerations. Each catalyst has its advantages and disadvantages, and the choice will depend on the specifics of the biodiesel production process being considered.

1.4 Preparation of biodiesel

Biodiesel is prepared by transesterifying vegetable oils or animal fats with methanol in the presence of a catalyst (such as sodium hydroxide), followed by separating and purifying the resulting biodiesel from glycerol and impurities. After purification, the biodiesel is ready for use as a sustainable and environmentally friendly alternative to conventional diesel fuel, offering reduced greenhouse gas emissions and dependence on fossil fuels.

1.4.1 Reaction mechanism

Transesterification reaction is a chemical process used to transform triglycerides (the main component of vegetable oils and animal fats) into FAME (the main component of biodiesel). This process creates a renewable and potentially sustainable alternative to fossil fuels. The reaction needs an alcohol-type reactant (methanol or ethanol) and a catalyst (a base such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) or an acid such as sulphuric acid (H_2SO_4) or hydrogen chloride (HCL) or even an enzymatic catalyst such as lipase) to boost the reaction. The catalyst is dissolved in the alcohol by an agitator and then placed in the flask, which the oil is added. The reaction is performed at a temperature between 60 to 70°C and it takes around three hours to complete with ratio alcohol to oil (1:3) (Mandari et Devarai 2022).

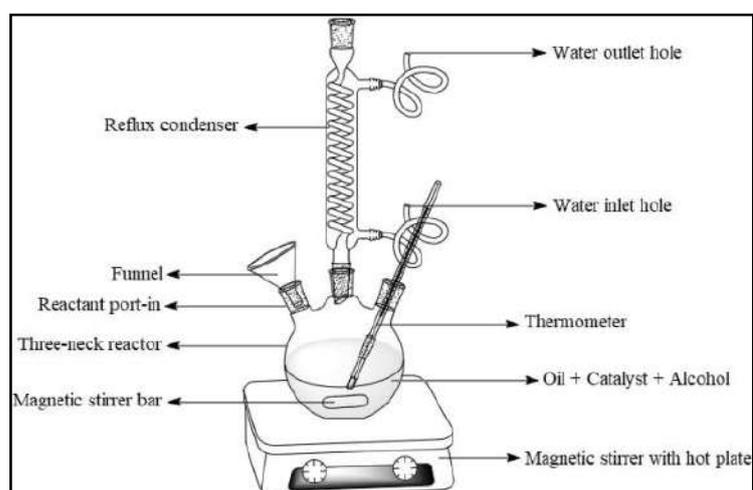


Figure 5: Scheme of the experimental apparatus for the transesterification reaction process.

1.4.2 The separation and purification

The reaction produces two new products, glycerol and biodiesel (ester) which are placed in the centrifuge to speed up the separation. Glycerol is denser than biodiesel, so the two phases can be separated by gravity by drawing off the glycerol from the underside of decanting funnel. After 24h of the decantation, the biodiesel should be washed with warm water to remove the catalyst and alcohol residues. The biofuel is purified by evaporation or distillation to remove the excess alcohol. The recycled alcohol is then reused in the process.

1.4.3 Glycerol neutralization

The catalyst is neutralized using an acid, which produces crude glycerol with a purity of between 80% and 88%. Glycerol at this stage may contain water, soaps, alcohol and traces of unused catalyst. For specific needs (pharmaceutical and cosmetics markets), glycerol is distilled to obtain a degree of purity higher than the 99% required.

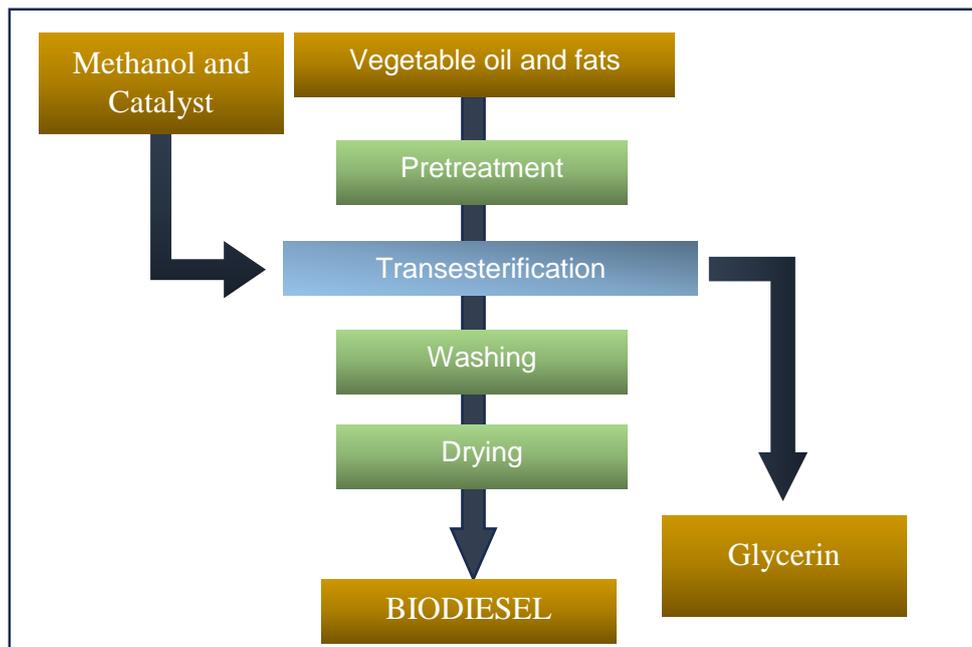


Figure 6: Preparation steps of the biodiesel production.

1.5 Transesterification reagents

Transesterification reagents typically include an alcohol (such as methanol or ethanol), a catalyst (either a base like sodium hydroxide, an acid like sulfuric acid, or an enzyme like lipase), and sometimes a solvent.

1.5.1 Triglycerides

Vegetable oils are mainly composed of around 95% glycerides (mainly triglycerides (TG), monoglycerides (MG) and diglycerides (DG)) and 5% secondary compounds (Free fatty acids (FFA), waxes, vitamins A, D and E and various hydrocarbons)

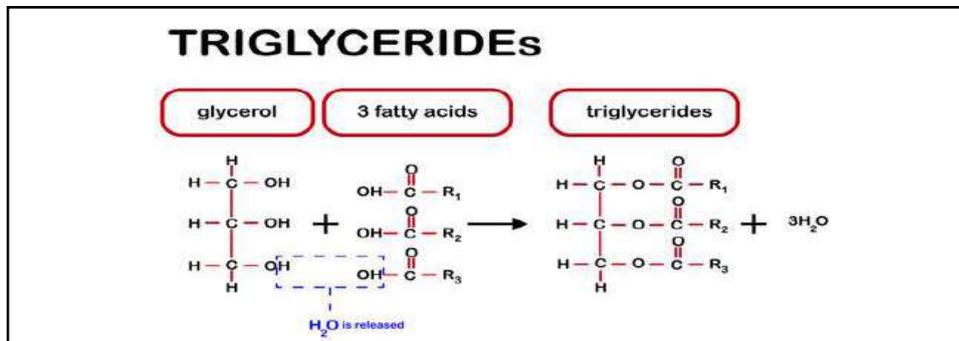


Figure 7: Chemical structure of Mono-, Di- and Tri-Glycerides.

A triglyceride is made up of a glycerol molecule (a molecule with three alcohol functions) esterified with three similar or different fatty acid molecules.

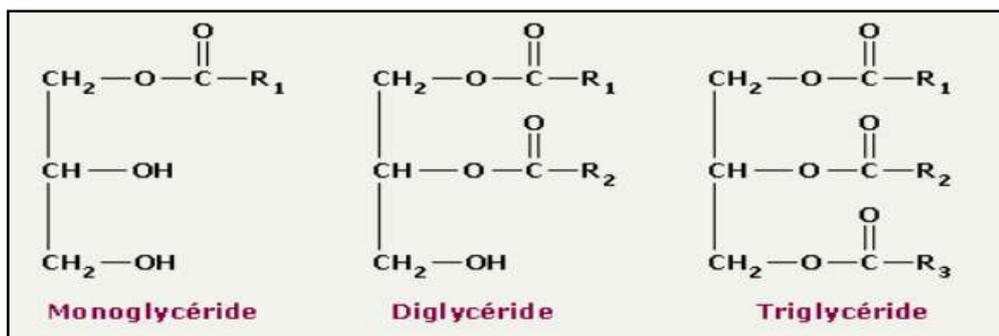


Figure 8: Reaction mechanism of triglycerides.

1.5.2 Methyl or ethyl esters of biodiesel

Methyl esters are liquid biofuels obtained through chemical processes from vegetable oils or animal fats and an alcohol. The production of methyl esters involves transesterification, a process where vegetable oils are reacted with methanol in the presence of a catalyst. This reaction converts the triglycerides in the oils into fatty acid methyl esters, which are the key components of biodiesel.

1.6 Types of catalysts

Catalysts can significantly increase the reaction rate, which allows it to be performed in a shorter time. There are many types of catalyst such as acidic and basic catalysts in a homogenous phase or heterogeneous one.

In our study, the catalysts used are Sodium hydroxide (KOH) as a base catalyst, Sulphuric acid (H₂SO₄) as an acid catalyst and lipase as an enzymatic catalyst.

1.6.1 Sodium hydroxide (KOH)

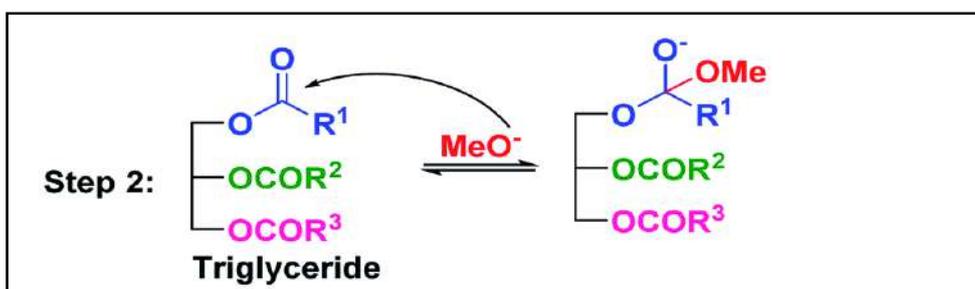
Sodium hydroxide is an efficient basic catalyst due to its high basicity. It is a relatively selective catalyst that it favors the formation of the desired product.

The transesterification reaction mechanism by KOH is described in three steps:

- Alcohol deprotonating: Potassium hydroxide (KOH) deprotonates the alcohol, forming an alkoxide ion



- Nucleophilic attack of the alkoxide ion on the ester: The alkoxide ion attacks the carbonyl group of the ester, forming a tetrahedral intermediate.



- the production of the alkyl group: The tetrahedral intermediate decomposes, releasing the alkyl group R^1 and forming a new ester.

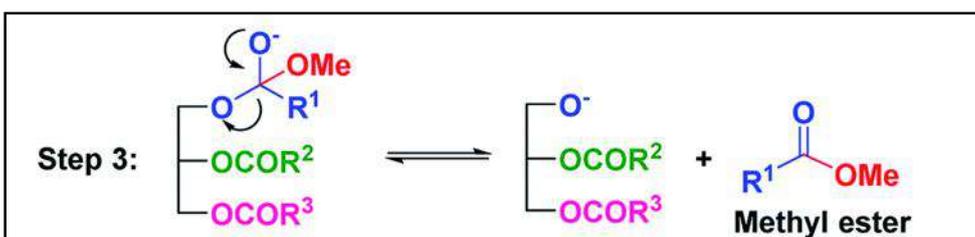


Figure 9: Mechanism of the transesterification reaction with KOH.

1.6.2 Sulphuric acid (H_2SO_4)

There are certain advantages to choosing an acid catalyst, such as the absence of the saponification reaction, which inhibits the transesterification reaction (as in the basic catalysis case). In addition, acidic materials are capable of catalyzing the transesterification and esterification reactions of the oil into biodiesel simultaneously, even in the presence of a high quantity of free fatty acids.

The transesterification reaction with H_2SO_4 involves the following steps:

- Protonation of the ester: H_2SO_4 donates a proton to the carbonyl oxygen of the ester, making it more electrophilic.
- Nucleophilic attack by the alcohol: The alcohol attacks the electrophilic carbon atom of the protonated ester.
- Deprotonation: The intermediate formed in step 2 is deprotonated by a base, typically water or another molecule of the alcohol.
- Product formation: The final product, a new ester is formed (Ashenhurst 2022).

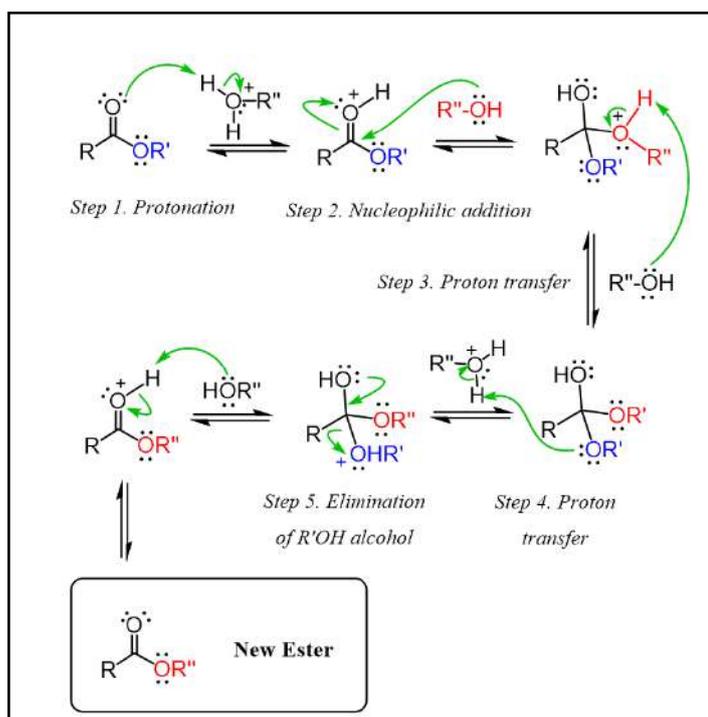


Figure 10: Mechanism of the transesterification reaction with H_2SO_4 .

1.6.3 Enzymatic catalyst (lipase)

In the last decade, the research on enzymatic catalysis in transesterification reactions has developed considerably, with particular emphasis on the use of lipase. This enzyme has emerged as a promising alternative to traditional chemical catalysts due to its many advantages, including high selectivity, mild reaction conditions, environmental friendliness and reusability.

The transesterification reaction with lipase involves protonation, nucleophilic attack, acyl transfer, and is influenced by factors like water content and the choice of lipase catalyst to ensure efficient conversion of substrates into ester products (Meir et al. 2022).

1.7 Experimental conditions

Many factors affect the transesterification reaction process, such as time and temperature, the alcohol/oil molar ratio, the type and quantity of catalyst, etc.

1.7.1 Reaction temperature

The significant influence of temperature on transesterification is an important consideration. As the temperature increases, the rate of the reaction accelerates, resulting in improved conversion efficiencies and reduced reaction times. This highlights the importance of determining the optimum temperature that balances conversion yield with the operational parameters of the transesterification process (Verma et Sharma 2016).

Freedman (Freedman, Pryde, et Mounts 1984) studied three temperatures for the transesterification of refined soya oil with methanol (6: 1) using 1% NaOH. After 6 min, ester yields were 94, 87 and 64% at 60, 45 and 32°C, respectively. After 1h, ester formation was similar for the 60 and 45°C assays and the yield was 98%. The reaction temperature influenced the reaction rate and ester yield.

1.7.2 Reaction time

The impact of time on the transesterification reaction is indeed important. Studies have shown that the reaction time plays a crucial role in determining the biodiesel yield and conversion rate.

Siddharth Jain investigated the production of biodiesel from *Jatropha curcas* oil through transesterification. The study examined the reaction at various temperatures and reaction times, including 5, 50, 120, and 180 minutes. The maximum biodiesel yield achieved was 90.1%, obtained after 180 minutes of reaction time at an optimum temperature of 50°C (Jain et Sharma 2010).

1.8 Biodiesel characteristics

The transition from oil to its ester form shows that the process involves changes in physical characteristics that make them resemble true diesel fuels. The European standard EN 14214 and the American standard ASTM D 6751 regulate these chemical and physical properties to ensure the quality and performance of biodiesel fuels (Yasin et al. 2013). These standards set specifications for parameters like cetane number, density, flash point, and biodiesel content, ensuring consistency and quality in biodiesel production. The properties of Fatty Acid Methyl Esters (FAME), which are esters of fatty acids commonly used as biodiesel, exhibit similarities to conventional diesel, making them a viable renewable alternative fuel with properties suitable for use in engines (Lin et Wu 2022).

1.8.1 Chemical structure

Recently biodiesel has been widely used as an alternative fuel. Biodiesel quality analysis has become very important because consistency and a higher quality are paramount to the success of its commercialization and market acceptance (Portillo et al. 2015).

The infrared spectrum is a structural analysis technique that can be used to identify the developed structure of molecules. The most common purpose of this infrared spectrum is to identify the structure of the product (biodiesel). The instrument typically consists of a source of infrared radiation, a sample holder, a detector, and a data processing unit. Infrared spectrophotometers play a critical role in the examination of biodiesel because of their capacity to detect essential functional units such as esters in fatty acid methyl esters (FAME) (Zhang 2012a).

1.8.2 Viscosity

The viscosity of biodiesel, an important parameter defined in biodiesel standards, is determined at a temperature of 40°C. The viscosity of biodiesel slightly exceeds that of petrodiesel, in accordance with ASTM D975 and EN 590 standards (Tat et Van Gerpen 1999). This disparity in viscosity is important because of its influence on the fuel's ability to atomise and mix with air during combustion, which affects engine performance and efficiency (Knothe et Steidley 2007).

1.8.3 Cloud point

The cloud point (CP) is the temperature at which small solid crystals can be observed as the fuel cools. It is influenced by the feedstocks used to produce the biodiesel, with different feedstocks resulting in varying cloud points (D. S. Shrestha et al. 2005).

For instance, when looking at biodiesel derived from soybean oil, it is common to observe a cloud point of approximately 1°C, whereas biodiesel made from canola oil often has a cloud point of around 0°C.

1.8.4 Flash point

The flash point (FP) of fuels is a critical property that determines the minimum temperature at which the vapors of a fuel will ignite when exposed to an open flame or spark under specific test conditions (Stauffer, Dolan, et Newman 2008). This property is essential for ensuring the safe transportation, storage, and handling of fuels, as it directly affects the risk of fire and explosion. Experimental methodologies like closed cup and open cup methods are commonly used to measure the FP of petroleum products, but they can be costly and time-consuming (Santos et al. 2020).

1.8.5 Cetane index

The cetane number (CI) is a dimensionless number that characterizes the quality of biodiesel fuels by ignition benefit. It is estimated from the distillation or density curve of the fuel and it

is used to estimate the cetane number because of the need for a specific engine test to measure it (Mekonnen, Endris, et Abdu 2024).

1.8.6 Calorific value

The calorific value (CV) of biodiesel is a crucial parameter that represents the amount of heat energy released during the combustion of a specified quantity of the fuel. It is a measure of the energy content of biodiesel and is typically expressed in units of kilojoules per kilogram (kJ/kg) or kilocalories per gram (kcal/g).

The calorific value of biodiesel is determined experimentally using a bomb calorimeter under defined conditions. This process involves placing a known quantity of biodiesel in a sealed container, igniting it, and measuring the temperature rise of the surrounding water (Oliveira et Da Silva 2013).

1.8.7 Molar ratio oil/alcohol

The molar ratio of alcohol to oil is a key factor in the transesterification process for biodiesel production. It is defined as the ratio of moles of alcohol to moles of oil used in the reaction.

Determining the molar ratio involves considering several factors:

- **Stoichiometric conditions:** The stoichiometric molar ratio of alcohol to oil in transesterification is generally 3:1, but higher ratios are often used to improve miscibility and reaction efficiency.
- **Reaction conditions:** Factors such as the nature of the catalyst, temperature and type of feedstock influence the appropriate molar ratio for optimum biodiesel production.
- **Experimental optimization:** Empirical studies are carried out to identify the ideal molar ratios for specific feedstocks and alcohols, in order to maximize conversion efficiency and yield (Musa 2016).

Conclusion

Biodiesel production is an important alternative to fossil fuels as energy demand grows and fossil fuel reserves deplete. Biofuels are produced from vegetable oils or animal fats using a number of techniques, including transesterification. This reaction is influenced by a number of parameters, such as the type of oil used and its fatty acid composition, the oil/alcohol molar ratio, temperature, reaction time and catalyst concentration. The structural characteristics of the molecules that are present in biodiesel influence its physicochemical properties, such as viscosity, density, cetane number, etc. The effect of physicochemical properties on engine combustion properties can be studied using these parameters.

CHAPTER 02

EXPERIMENTAL PART

2.1 Materials and products

This chapter describes the equipment, experimental techniques used both in transesterification reaction from used cooking oil using methanol, with three types of catalyst (basic, acidic and enzymatic), and to determine the physico-chemical properties of the biofuels obtained.

Many experimental conditions influence the efficiency of esters and the quality of the product: the reaction temperature, the concentration of the catalyst and its type, the alcohol/oil molar ratio, the fatty acid content of the oil, the duration of the reaction, agitation, etc.

In our work, we will study the influence of catalysts on this reaction, setting the temperature at 60°C, the catalyst concentration at 1% of the oil mass and the oil/alcohol molar ratio at (1:3), the yield and the quality of the product will be measured.

2.1.1 Equipment

- Flask tri-colle (500 ml).
- Bechers (250ml).
- Thermometer.
- Graduated test tube.
- A balance.
- Hot plate with magnetic stirrer.
- Water bath.
- Cooler.
- Decanting funnel (500ml).
- Centrifuge.

2.1.2 Products

- Oil of soya (Elio® oil).
- Methanol.
- Potassium hydroxide.
- Sulphuric acid.
- Lipase.

2.2 The sampling

The raw material used in our study was a sample of used cooking oil (Elio® brand).

This oil is essentially composed of soya oil.



Figure 11: Commercialized Elio® oil and its composition.

Calculation of the approximate molar mass of Elio® oil

To calculate of the molar mass of the oil, we use the following equation:

$$x_{linoleic\ acid} = \frac{n_i}{n_T} = \frac{m_i}{M_i \times n_T} = \frac{w_i \times m_{Tot}}{M_i \times n_T} = \frac{w_{linoleic\ acid} \cdot m_{oil}}{M_{linoleic\ acid} \times \underbrace{n_T}_{0,733\ mol}}$$

$$x_{linoleic\ acid} = \frac{54. m_{Huile}}{280,45 \times 0,733} = 52,53 \%$$

$$x_{oleic\ acid} = \frac{23. m_{Huile}}{282,46 \times 0,733} = 24,14 \%$$

$$x_{palmitic\ acid} = \frac{11. m_{Huile}}{256,43 \times 0,733} = 11,67 \%$$

$$x_{linolenic\ acid} = \frac{8. m_{Huile}}{278,43 \times 0,733} = 7,83 \%$$

$$x_{stearic\ acid} = \frac{4. m_{Huile}}{284,48 \times 0,733} = 3,83 \%$$

The molar mass of the oil was:

$$M_{oil} = \frac{\sum x_i \times M_i}{100} = 278,21\ g/mol$$

Calculation the mass of methanol

To calculate of the molar mass of the methanol, we use the following equation:

$$m_{méthanol} = n_{méthanol} \times M_{méthanol} = 2,199 \times 32 = 70,36\ g$$

Calculation of the mass of KOH

The mass of KOH was obtained according to the following formula:

$$m_{KOH} = 0,01. m_{huile} = 2\ g$$

Calculation of the volume of H₂SO₄

The volume of acid (H₂SO₄) used in the transesterification reaction was calculated as follows:

$$V = 0.01 \left(\frac{m_{oil}}{d_{H_2SO_4} \times \rho_{H_2O}} \right) = 1.093ml$$

Calculation of the mass of lipase

The mass of KOH was obtained according to the following formula:

$$m = 0.08 \times m_{oil} = 16g$$

2.3 Operational process

2.3.1 Reactants mixture

The catalyst is dissolved in the methanol with stirring to obtain a homogeneous mixture and then poured in after heating the oil.



Figure 12: Reactants of transesterification reaction.

2.3.2 The reaction

The reaction is performed in a 500 mL tri-collar flask equipped with a refrigerant connected to a cooling system. A mass of oil is poured into the flask and heated using a stirred hot plate until the temperature reaches 60°C, at which point the catalyst solubilized in methanol is added. The duration of the reaction is 2 hours. The experiment is repeated several times, with different types of catalyst.



Figure 13: Transesterification reaction process.

2.3.3 Decanting

At the end of each experiment, the reaction mixture is placed in a centrifuge for 30min.

It is necessary to separate the heterogeneous mixture by decanting. The reaction generates two new products, glycerol and biodiesel. Glycerol, characterized by its brown color, exhibits a higher density compared to biodiesel, causing it to accumulate at the bottom of the container.

The following step involves the separation of the two phases by removing the glycerol from the lower portion of the separating funnel



Figure 14: Decantation process.

2.3.4 The wash and purification

After decanting, the biodiesel is washed by warm water then placed in the oven at 100°C for 2 hours to eliminate any traces of methanol and water. The mass of biodiesel is then measured and its yield calculated using the following formula:

$$R = \frac{m_B}{m_{oil}} \times 100$$

Which:

m_B : Mass of biodiesel obtained.

m_{oil} : Mass of oil used.



Figure 15: The reaction products.

2.4 Type of catalyst used

2.4.1 Basic catalyst

The basic catalyst used in the production is potassium hydroxide, the KOH catalyst supported on activated carbon demonstrates good stability and reusability in transesterification reactions, with minimal decay in catalytic activity over multiple uses (Baroutian et al. 2010). Here are the key properties of KOH:

- Appearance: White, waxy solid;
- Molecular Weight: 56.11 g/mol;
- Melting Point: 360°C (680°F);
- Boiling Point: 1,327°C (2,421°F);
- Solubility: Highly soluble in water, forming a strong basic solution.

2.4.2 Acid catalyst

The acid catalyst used in the transesterification process is sulphuric acid. The H_2SO_4 has the ability to be an effective catalyst, particularly when the raw materials are of low quality and contain high levels of free fatty acids (FFA) (Gebremariam et Marchetti 2018). Here are the key properties of H_2SO_4 :

- Appearance: Colorless, oily liquid;
- Molecular Weight: 98.08 g/mol;
- Melting Point: 10.4°C (50.7°F);
- Boiling Point: 337°C (639°F);
- Solubility: Highly soluble in water, forming a strongly acidic solution. It also dissolves in ethanol and diethyl ether.

2.4.3 Enzymatic catalyst

Lipase is employed as a catalyst in the process of transesterification reaction. This enzyme is preferred for biodiesel production due to his reusability, high yield, and minimal downstream processes compared to traditional catalysts (Jayaraman et al. 2020).

2.5 Physic-chemical properties

The physical properties of biodiesel change significantly compared to the original oil when it is converted to its corresponding ester. This makes the properties of biodiesel closer to those of petroleum diesel fuel. The European standard EN 14214 and American standard ASTM D 6751 specify and control the chemical and physical properties of biodiesel (Hannu, s. d.). Some key properties include:

2.5.1 Viscosity test

It is the measurement of gravity flow time of a volume of liquid in a calibrated capillary viscometer under a reproducible liquid load and at a controlled temperature. The kinematic viscosity is the product of the measured flow time and the viscometer calibration constant. This method is used to determine the kinematic viscosity of liquid, opaque and transparent products according to EN ISO 3104 (Tesfa et al. 2010).



Figure 16: Viscometer (Herzog HVM 472).

2.5.2 Calorific value

The calorific value is determined by burning a known quantity of sample in a calorimetric bomb containing an excess of oxygen under pressure. This value is calculated from the variation in temperature observed during combustion of the sample (Fassinou et al. 2010).



Figure 17: Calorimeter (IKA C200).

2.5.3 Flash point

The flash point test involves gently heating a sample at a constant rate of temperature increase and with continuous agitation. For each degree of temperature increase, a flame is introduced into the vapor produced above the sample. The lowest temperature at which the vapor ignites is the flash point (Mejía, Salgado, et Orrego 2013).



Figure 18: ASTM D93 Pensky-Martens Closed Cup.

2.5.4 Infrared spectrum

The infrared spectra were obtained using an Agilent Cary 660 FT-IR spectrophotometer. The spectrum of a substance can be recorded in a gaseous, liquid, solid or solution state. In this study, the liquid state was used: a film was deposited between two pellets of KBr or NaCl. Scanning the frequency range between 4000 and 600 cm^{-1} (Zhang 2012b).



Figure 19: IR spectrophotometer (Cary 660 FT-IR).

2.5.5 Cloud point

The cloud point is the temperature at which crystals first start to form in the fuel. It is reached when the temperature of the sample is low enough to cause wax crystals to precipitate. To determine the cloud point, a sample of each oil is put into a test tube containing a thermometer and sealed with a cork. The sample is then heated to within 46°C to 50°C and cooled in a series of cooling baths. The temperature at which a haze or cloud is first seen at the bottom of the test tube is noted as the cloud point (Cole 2017).



Figure 20: Cloud Point Analyzer (ASTM D2500, D5771).

2.5.6 Cetane index

When it comes to determining the cetane index of biodiesel, various methods are commonly used, and one of the most popular is the ASTM D613 test method. This particular method works by measuring the ignition quality of the fuel in a standardized engine test. This means that the test is designed to be consistent and fair, allowing for accurate comparisons between different fuels. The ASTM D613 method is widely used for determining the cetane index of all types of diesel fuels, including biodiesel (Bajpai et Tyagi 2006).



Figure 21: Fully-Automatic Cetane index Tester.

Conclusion

This chapter presents an overview about the experimental procedure adopted to prepare the biofuel using waste oil. The different materials and products used in this experimental were presented. The sample of the oil was identified and the operational process was described in this chapter with details. In addition, a brief description about the type of the catalyst was presented and the apparatus used for the physic-chemical analysis of the sample were presented and discussed.

CHAPTER 03

RESULTS AND DISCUSSION

3.1 Analysis results of basic catalyst

3.1.1 Viscosity

Viscosity is an important characteristic of fuels. It is highly dependent on temperature and has a direct influence on the operation of the injection system, especially at low temperatures.

Biodiesel produced by the basic catalyst (KOH) has viscosity value in the ASTM standard (maximum 6 mm²/s).

Biodiesel viscosity with KOH is **4.846 mm²/s**.

3.1.2 Cloud point

The use of KOH as a basic catalyst in the transesterification reaction gave a CP value higher than the ASTM standard limit (maximum 12°C).

Biodiesel with a cloud point higher than the norm can have serious consequences in terms of plugging fuel filters, which can lead to engine blocking or failure in cold conditions.

Biodiesel CP value with KOH is **42.979°C**.

3.1.3 Flash point

The flash point of biodiesel using the KOH catalyst is higher than the ASTM D 6751 norm (maximum 170°C).

The biodiesel obtained is therefore less flammable than standard ASTM biodiesel. This makes it a less dangerous biofuel to handle and it is guaranteed for storage.

Biodiesel FP value with KOH is **214°C**.

3.1.4 Cetane index

The cetane index of biodiesel produced was measured using the ASTM D613 test method; the value obtained is optimum to that of the ASTM standard (maximum 65).

The CI is an important quality parameter, and a reduction in it can lead to a deterioration in the biofuel's performance.

Biodiesel CI value with KOH is **62.753**.

3.1.5 Calorific value

The calorific value of biodiesel resulting is higher than the ASTM norm (maximum 37.3MJ/Kg).

The calorific value (CV) of biodiesel has a significant impact on its performance in diesel engines. The higher calorific value of biodiesel results in an increase in power and efficiency, as well as a reduction in fuel consumption.

Biodiesel CV value with KOH is **42.125 MJ/Kg.**

3.1.6 IR spectrum

The IR spectrum of biodiesel produced using a potassium hydroxide (KOH) catalyst highlights several functional groups indicative of the chemical composition of the biodiesel (Figure 22). Key absorption peaks observed in the IR spectrum include:

- **Symmetrical Trisubstituted Aromatic C-H Bending ($670-730\text{ cm}^{-1}$):**

Absorption bands in this region correspond to the C-H bending vibrations of trisubstituted aromatic rings. This suggests the presence of aromatic compounds within the biodiesel.

- **C-OH Stretching ($1150-1300\text{ cm}^{-1}$):**

Strong absorption bands within this range are associated with the C-OH stretching vibrations of aromatic alcohols. These peaks indicate the presence of phenolic compounds or other aromatic alcohols.

- **C=O Stretching ($1650-1740\text{ cm}^{-1}$):**

A strong peak in this region is characteristic of the carbonyl (C=O) stretching vibrations of esters and aliphatic aldehydes. This confirms the presence of ester functional groups, which are the primary constituents of biodiesel.

- **O-H Stretching ($2900-3300\text{ cm}^{-1}$):**

Broad absorption bands in this range are indicative of O-H stretching vibrations, typically from hydroxyl groups in carboxylic acids. This suggests that some free fatty acids or residual glycerol might be present in the biodiesel.

- **N-H Stretching ($3300-3500\text{ cm}^{-1}$):**

Absorption bands in this region are associated with the N-H stretching vibrations of primary amines. This indicates the possible presence of nitrogen-containing compounds, although they are not typically expected in high concentrations in biodiesel.

The IR spectrum thus provides a detailed fingerprint of the biodiesel produced using KOH as a catalyst, confirming the presence of various functional groups such as esters, aromatic

compounds, carboxylic acids, and possibly nitrogenous compounds. This analysis is essential for evaluating the quality and composition of the biodiesel.

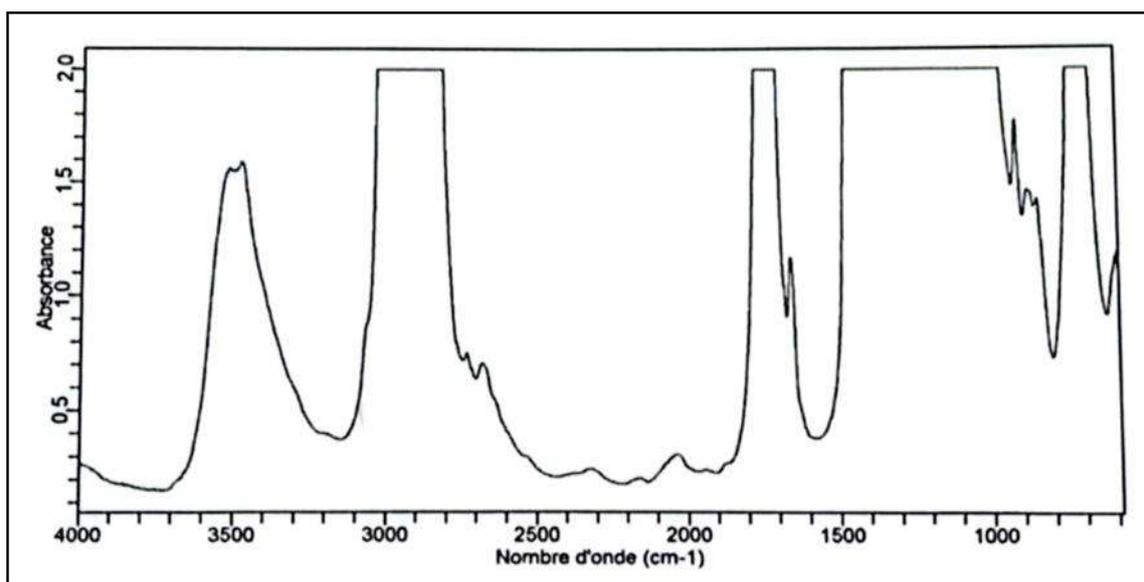


Figure 22: IR spectra of biodiesel for the KOH catalyst.

Table 1 summarizes the results obtained from the IR spectra of biodiesel produced by using KOH as catalyst.

Table 1: Functional groups of biodiesel IR spectrum for KOH catalyst.

Bond	Wave number	Intensity
Symmetrical trisubstituted aromatic C-H bond	between 670 and 730 cm^{-1}	Strong
C-OH aromatic alcohol bond	between 1150 and 1300 cm^{-1}	Strong
C=O bond of aliphatic aldehydes	between 1650 and 1740 cm^{-1}	Strong
O-H bond of carboxylic acids	between 2900 and 3300 cm^{-1}	Strong
N-H bond of primary amines	between 3300 and 3500 cm^{-1}	Medium

3.2 Analysis results of acid catalyst

3.2.1 Viscosity

Biodiesel viscosity is an essential property that affects fuel combustion and performance. Optimizing viscosity through fuel composition and temperature control is essential to maximize the efficiency of biodiesel in diesel engines.

Biodiesel produced by the acid catalyst (H_2SO_4) has viscosity value in the ASTM standard (maximum $6 \text{ mm}^2/\text{s}$).

Biodiesel viscosity with H_2SO_4 is **4.310 mm^2/s** .

3.2.2 Cloud point

The use of H_2SO_4 as an acid catalyst to produce biodiesel led to a CP value higher than the ASTM standard limit (maximum 12°C).

Biodiesel with an elevated cloud point poses a significant risk of clogging fuel filters, particularly in cold environments. This can result in engine stalling or complete failure due to fuel starvation.

Biodiesel CP value with H_2SO_4 is **51.704 $^\circ\text{C}$** .

3.2.3 Flash point

The H_2SO_4 catalyst significantly improves the flash point of biodiesel, exceeding the maximum limit of 170°C set by ASTM D 6751.

This high flash point indicates a reduction in flammability compared to standard ASTM biodiesel, making the catalyst a safer choice for handling and long-term storage.

Biodiesel FP value with H_2SO_4 is **180 $^\circ\text{C}$** .

3.2.4 Cetane index

The ASTM D613 test method was used to determine the cetane index of the biodiesel produced, which gave a value perfectly corresponding to the maximum value of 65 set by the ASTM standard.

As the cetane index is an important indicator of biodiesel quality, any reduction below this value may result in inferior performance.

Biodiesel CI value with H₂SO₄ is **62.451**.

3.2.5 Calorific value

The biodiesel produced has a calorific value higher than the maximum limit of 37.3 MJ/kg set by the ASTM specification.

This high calorific value considerably improves the performance of biodiesel in diesel engines, resulting in increased engine power and efficiency.

Biodiesel CV value with H₂SO₄ is **42.415 MJ/Kg**.

3.2.6 IR spectrum

The IR spectrum of biodiesel produced using a sulfuric acid (H₂SO₄) catalyst reveals several characteristic functional groups (Figure 23). These functional groups correspond to various vibrations and bonds present in the biodiesel molecules. The key absorption peaks observed in the IR spectrum include:

- **C-H Stretching (2850-3000 cm⁻¹):**

Strong absorption bands are observed in this region, corresponding to the C-H stretching vibrations. These are typical of aliphatic hydrocarbons, indicating the presence of long-chain fatty acid methyl esters, which are the main components of biodiesel.

- **C=O Stretching (1660-1740 cm⁻¹):**

A strong peak in this region indicates the presence of carbonyl (C=O) groups, which are characteristic of ester functional groups. This confirms the successful transesterification of triglycerides into methyl esters, a key reaction in biodiesel production.

- **C-O Stretching (1170-1300 cm⁻¹):**

The presence of strong absorption bands in this range is indicative of C-O stretching vibrations. These peaks are associated with ester bonds, specifically the aromatic ether (Ph-O-) linkages, suggesting that some aromatic compounds might be present in the biodiesel.

- **O-H Stretching ($2900-3300\text{ cm}^{-1}$):**

The broad absorption bands in this range are indicative of O-H stretching vibrations. These bands are typically associated with hydroxyl groups from carboxylic acids, suggesting that free fatty acids or residual glycerol might be present in the biodiesel.

The combination of these absorption bands provides a comprehensive fingerprint of the biodiesel produced using H_2SO_4 as a catalyst, confirming the presence of ester functional groups along with some free fatty acids and possibly other oxygenated compounds. This detailed IR spectral analysis is crucial for assessing the quality and composition of biodiesel.

Strong absorption bands are observed in this region, corresponding to the C-H stretching vibrations. These are typical of aliphatic hydrocarbons, indicating the presence of long-chain fatty acid methyl esters, which are the main components of biodiesel.

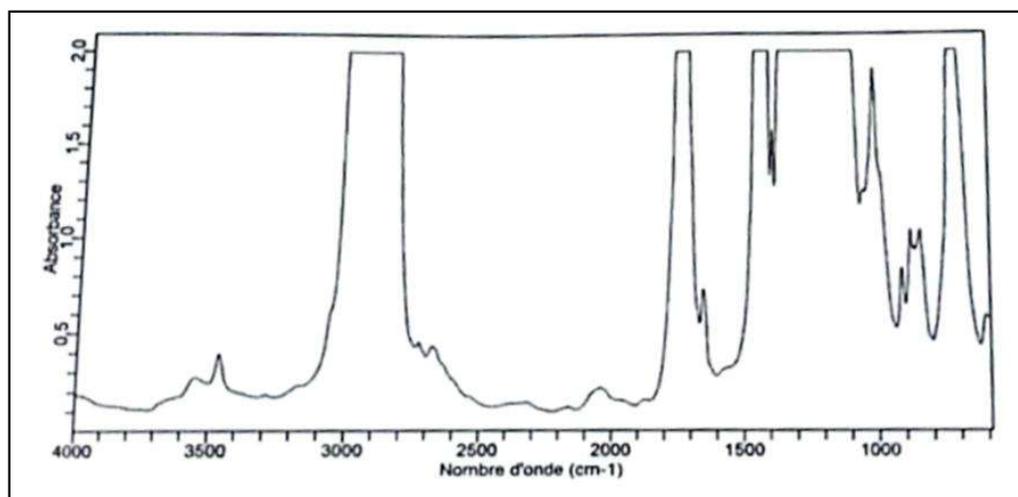


Figure 23: IR spectra of biodiesel for the H_2SO_4 catalyst.

Table 2 summarizes the results obtained from the IR spectra of biodiesel produced by using H_2SO_4 as catalyst.

Table 2: Functional groups of biodiesel IR spectrum for H_2SO_4 catalyst.

Bond	Wave number	Intensity
C-H bond	from 2850 to 3000 cm^{-1}	Strong
C-O bond of aromatic ethers (Ph-O-)	between 1170 and 1300 cm^{-1}	Strong
C-H bond of CHO	between 2700 and 2900 cm^{-1}	Medium
O-H bond of carboxylic acids	between 2900 and 3300 cm^{-1}	Strong
C=O Bond of Carboxylic Acids	between 1660 and 1740 cm^{-1}	Strong
O-H bond of carboxylic acids	between 2900 and 3300 cm^{-1}	Strong

3.3 Analysis results of enzymatic catalyst

3.3.1 Viscosity

Viscosity represents a fundamental factor in the properties of fuels, varying greatly with temperature and having a direct impact on the functionality of the injection system, particularly in colder conditions.

Biodiesel produced using an enzymatic catalyst (lipase) has a viscosity above the ASTM standard limit of $6\text{mm}^2/\text{s}$.

Biodiesel viscosity with lipase is **7.987 mm²/s**.

3.3.2 Cloud point

Using lipase as an enzymatic catalyst in the transesterification reaction gave a CP value in the ASTM standard norm (maximum 12°C)

Biodiesel produced with a normal cloud point, according to ASTM standards, its low temperature operation provides reliable performance in colder climates while reducing the impact on the environment.

Biodiesel CP value with lipase is **-0.290°C**.

3.3.3 Flash point

The flash point of biodiesel while using lipase catalyst is too higher than the ASTM D 6751 limit (maximum 170°C).

As a result, the biodiesel formed is less flammable than standard ASTM biodiesel. This characteristic makes it a safer biofuel to handle and guarantees its suitability for storage.

Biodiesel FP value with lipase is **314.845°C**.

3.3.4 Cetane index

The lipase-catalyzed biodiesel was tested for its cetane index using the ASTM D613 method, and the obtained value meets the ASTM standard (maximum 65).

The cetane index is an essential quality parameter, and any decrease in it can lead to a lowering of the biofuel's performance.

Biodiesel CI value with lipase is **64.982**.

3.3.5 Calorific value

The calorific value of using lipase in biodiesel resulting is slightly higher than the ASTM norm (maximum 37.3MJ/Kg).

The calorific value is a critical factor in determining the performance of biodiesel in diesel engines. A higher calorific value leads to an increase in the power of a motor, with more energy available to run the process.

Biodiesel CV value with lipase is **41.416MJ/Kg.**

3.3.6 IR spectrum

The IR spectrum of biodiesel produced using a lipase biocatalyst showcases several distinct functional groups, reflecting the specific chemical composition of the biodiesel (Figure 24)..

Key absorption peaks observed in the IR spectrum include:

- **C-O Stretching of Esters (1210-1260 cm^{-1}):**

Strong absorption bands in this region correspond to the C-O stretching vibrations of esters. These peaks are indicative of the ester functional groups, confirming the successful conversion of triglycerides into fatty acid methyl esters, which are the primary components of biodiesel.

- **Ionized Carboxylic Acids (1400-1450 cm^{-1}):**

A strong peak in this range is associated with the symmetric stretching vibrations of ionized carboxylate (COO^-) groups. This suggests the presence of ionized carboxylic acids, which might be due to partial saponification or the presence of free fatty acids.

- **C-O Stretching of Carboxylic Acids (1200-1320 cm^{-1}):**

Absorption bands in this region are also indicative of C-O stretching vibrations in carboxylic acids. This further confirms the presence of carboxylic acid functional groups, possibly from residual free fatty acids or intermediate products in the biodiesel.

The IR spectrum thus provides a detailed fingerprint of the biodiesel produced using a lipase biocatalyst. The presence of ester groups, ionized carboxylic acids, and carboxylic acids confirms the effective enzymatic transesterification process and provides insights into the purity

and composition of the final biodiesel product. This analysis is crucial for assessing the quality and chemical characteristics of the biodiesel.

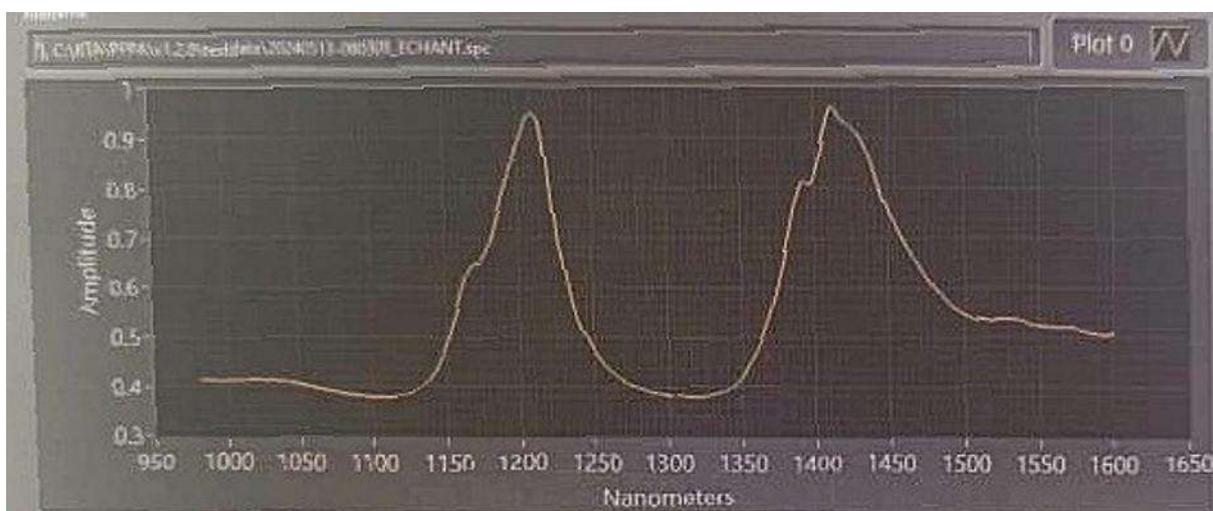


Figure 24: IR spectra of biodiesel for the lipase catalyst.

Table 3 summarizes the results obtained from the IR spectra of biodiesel produced by using H_2SO_4 as catalyst.

Table 3: Functional groups of biodiesel IR spectrum for lipase catalyst.

Bond	Wave number	Intensity
C-O bond of esters	between 1210 and 1260 cm^{-1}	Strong
ionised carboxylic acids	between 1400 and 1450 cm^{-1}	Strong
C-O bond of carboxylic acids	between 1200 and 1320 cm^{-1}	Strong

3.4 Physicochemical properties of biodiesel

Biodiesel produced using basic, acid, and enzymatic catalysts shows varying physicochemical properties, with enzymatic catalysts generally providing better cold flow properties, higher flash points, and slightly improved cetane indices and purity compared to basic and acid catalysts, all while meeting ASTM D6751 standards for viscosity, cloud point, flash point, cetane index, and calorific value.

Table 4: Biodiesel properties with different catalysts.

Samples	Basic catalyst	Acid catalyst	Enzymatic catalyst	Biodiesel (ASTM D6751)
Viscosity 40°C (mm²/s)	4.846	4.310	7.987	1.9 – 6
Cloud point (°C)	42.979	51.704	-0.290	Report
Flash point (°C)	214	180	314.845	100 – 170
Cetane index	62.753	62.451	64.982	48 – 65
Calorific value (MJ/kg)	42.125	42.415	41.416	37.3

3.4.1 Viscosity

According to ASTM standards, the kinematic viscosity of biodiesel varies between 1.9 mm²/s and 6 mm²/s.

The highest value of kinematic viscosity found is 7.987 mm²/s when using the enzymatic catalyst, meanwhile using the acid catalyst and the basic catalyst gives values in the range of standards (4.310 and 4.846 mm²/s).

3.4.2 Cloud point

The different catalysts used to produce biodiesel give different fatty acid compositions, which is the reason the CP of the biodiesel obtained varies according to the change of catalyst.

The standard method for determining CP (for biodiesel) is specified in ASTM D2500 within a range of -3°C to 12°C. According to the table, the highest CP values are 51.704°C and 42.979°C when using the acidic and basic catalysts. The use of enzymatic catalyst gives a value that is in the range of standards (-0.290°C).

3.4.3 Flash point

The method for the evaluation of FP specified in ASTM D93. Based on the table, the lowest value of FP is 180°C that is for biodiesel produced by the acid catalyst, and utmost value is 314.845 °C, that is for biodiesel obtained by the enzymatic catalyst.

The three FP values are very high compared with the minimum temperatures recommended in the American standard (100 - 170°C), which reflects safety during storage and use of the biodiesel synthesized.

3.4.4 Cetane index

A high cetane index (CI) indicates the fuel's ability to self-ignite rapidly after being transferred to the combustion chamber. For biodiesel, the cetane index increases with the degree of saturation and the length of the fatty acid chain. Biodiesel has a higher cetane index because it contains more oxygen and therefore has a higher combustion efficiency. The cetane index of biodiesel is determined by the ASTM D613 standard.

The lowest value obtained is 62.451 where the acid catalyst is used. Biodiesel produced using the enzymatic catalyst has the highest CI of 64.982, and the base catalyst in the biodiesel produced has a CN of 62.753.

3.4.5 Calorific value

Under ASTM standards, the calorific value of biodiesel is 37.3 MJ/Kg. The biodiesel produced using the basic catalyst gave the lowest calorific value compared to the biofuels studied, with 42.125 MJ/Kg. The use of acid and enzymatic catalysts to produce biodiesel gave similar calorific values, at 42.415 MJ/Kg and 42.416 MJ/Kg respectively.

3.5 Yield calculation

According to (Sinha et Madavi 2021) and other articles, the yield of the reaction is calculated by the following formula:

$$\text{Biodiesel yield: } R = \frac{m_{ester}}{m_{oil}} * 100$$

The following parameters were fixed to obtain the best yield from the catalysts used (reaction time, molar ratio and reaction temperature):

The maximum biodiesel yield is 90% corresponding to the basic catalyst. The biodiesel yield is 86% for the acid catalyst and 76 % for the enzymatic catalyst. The results show that the basic catalyst gives the best biodiesel yield.

GENERAL CONCLUSION

GENERAL CONCLUSION

Biodiesel has been established as a highly efficient alternative to fossil fuels due to its renewable, biodegradable, and non-toxic nature, particularly when produced from waste materials. Used cooking oil, especially soy oil, has significant potential as a biodiesel feedstock because of its abundant daily production worldwide.

However, utilizing cooking oil requires a pre-treatment process to remove solid impurities and reduce volatile fatty acid and water content. This study aimed to synthesize biodiesel from used soy oil, focusing on the influence of the catalyst type on the transesterification reaction yield. The duration, temperature, and oil/alcohol molar ratio were kept constant, while three different catalysts were tested to determine their impact on yield and quality.

The results indicated that the highest yield, 90%, was achieved using KOH as a basic catalyst. However, the physico-chemical analysis of the biodiesel samples revealed that the product obtained with an acid catalyst had the most favorable properties—viscosity, flash point, cetane number, and calorific value—meeting ASTM D6751 standards, though it exhibited a high cloud point.

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Abstract: The use of biodiesel is crucial as a sustainable and environmentally friendly alternative to fossil fuels due to its renewable, biodegradable, and non-toxic characteristics. This study analyzed various parameters affecting biodiesel quality, including the type of catalyst used in the transesterification process. By keeping the reaction duration, temperature, and oil/alcohol molar ratio constant while varying the catalyst type, the research determined that KOH as a basic catalyst produced the highest yield of 90%. However, the biodiesel synthesized with an acid catalyst exhibited the most favorable physico-chemical properties, such as viscosity, flash point, cetane number, and calorific value, aligning well with ASTM D6751 standards, despite its high cloud point. **Keywords :** biodiesel, catalysts, transesterification, physico-chemical properties, enzyme.

Résumé : L'utilisation du biodiesel est cruciale en tant qu'alternative durable et respectueuse de l'environnement aux combustibles fossiles en raison de ses caractéristiques renouvelables, biodégradables et non toxiques. Cette étude a analysé divers paramètres affectant la qualité du biodiesel, notamment le type de catalyseur utilisé dans le processus de transestérification. En maintenant constants la durée de la réaction, la température et le rapport molaire huile/alcool tout en faisant varier le type de catalyseur, la recherche a déterminé que le KOH en tant que catalyseur basique produisait le rendement le plus élevé de 90 %. Cependant, le biodiesel synthétisé avec un catalyseur acide présentait les propriétés physico-chimiques les plus favorables, telles que la viscosité, le point d'éclair, l'indice de cétane et le pouvoir calorifique, conformes aux normes ASTM D6751, malgré son point de trouble élevé. **Mots clés :** biodiesel, catalyseurs, transestérification, propriétés physico-chimiques, enzyme.

Arabic

المخلص: يعد استخدام وقود الديزل الحيوي أمرًا بالغ الأهمية كبديل مستدام وصديق للبيئة للوقود الأحفوري نظرًا لخصائصه المتجددة والقابلة للتحلل وغير السامة. قامت هذه الدراسة بتحليل العوامل المختلفة التي تؤثر على جودة وقود الديزل الحيوي، بما في ذلك نوع المحفز المستخدم في عملية الأسترة التبادلية. ومن خلال الحفاظ على ثبات مدة التفاعل ودرجة الحرارة والنسبة المولية للزيت/الكحول مع تغيير نوع المحفز، حدد البحث أن KOH كمحفز أساسي أنتج أعلى عائد بنسبة 90%. ومع ذلك، فإن وقود الديزل الحيوي المُصنَّع باستخدام محفز حمضي أظهر أفضل الخصائص الفيزيائية والكيميائية، مثل اللزوجة، ونقطة الوميض، ورقم السيتان، والقيمة الحرارية، بما يتماشى جيدًا مع معايير ASTM D6751، على الرغم من نقطة السحاب العالية. **الكلمات المفتاحية:** وقود الديزل الحيوي، المحفزات، الأسترة التبادلية، الخواص الفيزيائية والكيميائية، الإنزيم.