# PERFORMANCE CHARACTERISTICS OF THE BLEND OF 20% BIODIESEL TO 80% PETROL DIESEL IN A COMPRESSION IGNITION ENGINE

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**OCTOBER, 2025.**

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**A PROJECT SUBMITTED TO THE DEPARTMENT OF CHEMICAL ENGINEERING, FACULTY OF ENGINEERING, UNIVERSITY OF BENIN, BENIN CITY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF BACHELOR' DEGREE IN CHEMICAL ENGINEERING**

**(B.ENG.)**

**OCTOBER, 2025.**

## CERTIFICATION

This is to certify that this research project was carried by **OKONYE PRINCE IFEAKACHUKWU** with matriculation number **ENG2002063** in the Department of Chemical Engineering, University of Benin, Benin City, Edo State Nigeria.

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## DEDICATION

I dedicate this project work to the Almighty God, whose grace, wisdom and strength have guided me throughout this journey.

I also dedicate this project to my dearest mother, Mrs Comfort Ossai Okonye for her continuous and endless love, support and prayers.

## ACKNOWLEDGEMENT

I am deeply grateful to Almighty God for His divine guidance, wisdom and strength throughout the course of this project. Without His grace, this accomplishment would not have been possible.

My special thanks and deepest appreciation goes to my supervisor, Engr. Prof. (Mrs.) E.T Akhihiero, for her motherly assistance, love, care, immeasurable support, and professional insight, which contributed immensely to the success of this work.

My heartfelt appreciation goes to my parents Mr. and Mrs. P.C Okonye for their endless love, prayers, and sacrifices, which have remained my greatest source of motivation. I love you Mum and Dad. I also wish to express my sincere gratitude to my mentor, Mr. Dickson Okonye, for his constant encouragement, wise counsel, and support that greatly inspired me throughout this journey. I would not forget my siblings, Nkem, Judith, Chika, Anwuli, Ishioma and Gideon, for their understanding and support.

I also want to use this medium to appreciate my good friends, course mates and well wishers that one way or the other contributed to the success of this work.

## ABSTRACT

The global depletion of fossil fuels and rising environmental concerns have intensified research into renewable and sustainable fuel alternatives. This study investigates the performance characteristics of a 20 percent biodiesel and 80 percent petrol diesel blend (B20) as a potential substitute for diesel fuel in compression ignition engines.

The Waste Cooking Oil was collected, pretreated through acid-catalyzed esterification to reduce its free fatty acid content, blended with conventional diesel, and characterized based on viscosity, density, flash point, calorific value, and cetane number. Its suitability was assessed through comparison with biodiesel standards and published experimental data. The waste cooking oil was esterified to reduce its free fatty acid content before blending and laboratory analyses were conducted to evaluate the physicochemical properties of the 20:80 blend. Engine performance indicators such as brake power, fuel consumption, brake thermal efficiency (BTE), and exhaust gas emissions were carried out and results were compared with literature based datas.

The results from the findings revealed that the blends achieved a progressive yield with the B20 blend achieving the most stable yield with a calorific value of 42.05 MJ/kg, density of 0.8624, and a fuel consumption rate of 1316.64 g/hr, indicating a close match with conventional diesel fuel. The B20 blend also demonstrated improved brake thermal efficiency and lower emissions, particularly in nitrogen oxides (NOx) and sulfur dioxide ($SO_2$), due to enhanced combustion from biodiesel's oxygenated structure. This establishes the fact that the biodiesel-petrol blends, particularly the B20 is a technically viable, cost-effective, and environmentally sustainable alternative to petrol diesel.

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# CHAPTER ONE

# INTRODUCTION

## 1.1. BACKGROUND OF STUDY

Over the past few decades, there has been an intensified global focus on combating the adverse effects of climate change, particularly the role that greenhouse gas emissions play in accelerating global warming (Elkelawy et al., 2020; Kumar et al., 2025). The excessive dependence on fossil fuels for energy generation has significantly disrupted the Earth's natural climate systems (D. Singh et al., 2021), resulting in harmful consequences for human health (Akhihiero, 2022), agricultural productivity (Jagtap et al., 2020), water accessibility, and socioeconomic development (Aydın, 2020). Global institutions and scientific bodies continue to raise alarms over the increasing prevalence of diseases such as malaria, respiratory infections, and cardiovascular complications, which are directly linked to air pollution and rising temperatures caused by industrial emissions (Chen et al., 2024; Jagtap et al., 2020). In addition, the depletion of the ozone layer, rising sea levels, and deteriorating soil conditions have collectively threatened food security and access to clean water (Bolan et al., 2024).

A major contributor to this crisis is the combustion of fossil fuels such as coal, petrol, and diesel which not only produce large volumes of carbon dioxide but also release harmful pollutants such as sulfur oxides, nitrogen oxides, and particulate matter (Jagtap et al., 2020; Naseef & Tulaimat, 2025). These emissions degrade air quality, reduce biodiversity, and endanger the health of both humans and wildlife (Bolan et al., 2024). According to Barnett-Itzhaki & Levi (2021), over 4.2 million premature deaths globally each year are linked to ambient air pollution, with the majority of the population living in areas that exceed recommended air quality limits (Barnett-Itzhaki &

Levi, 2021). Thus, the need for cleaner, safer, and more sustainable energy alternatives has become a pressing global concern.

Among various renewable energy options, biodiesel has emerged as a practical and eco-friendly substitute for conventional diesel (Kumar et al., 2025). Biodiesel is produced through the transesterification of vegetable oils, either virgin or waste, into Fatty Acid Methyl Esters (Salaheldeen et al., 2021). This process reduces the inherent drawbacks of raw oils such as high viscosity, low volatility, and the tendency to form carbon deposits in diesel engines (Wan Osman et al., 2024). Importantly, biodiesel is non-toxic, biodegradable, and produces fewer greenhouse gases, making it an attractive candidate for reducing the transportation sector's carbon footprint (Gharehghani & Pourrahmani, 2019). Moreover, the unique properties of biodiesel, including its high flash point, superior lubricity, and compatibility with conventional diesel engines, allow it to be used either in pure form or in blends with petroleum diesel. These blends can be used without significant modifications to existing compression ignition engines. This compatibility not only simplifies implementation but also reduces costs associated with infrastructure overhaul (Wan Osman et al., 2024).

Of growing interest is the utilization of waste vegetable oils for biodiesel production (Singh et al., 2021). Recycling used cooking oils into biodiesel addresses two challenges simultaneously. First, it reduces the environmental hazards posed by improper disposal of waste oils. Second, it helps to cut down on the importation of fossil diesel, especially in developing countries such as Nigeria, where foreign oil dependence poses economic risks (Okpo & Edafiadhe, 2024). Furthermore, the conversion of waste vegetable oil into fuel adds value to waste, fosters circular economy principles, and strengthens national energy security (Okpo & Edafiadhe, 2024). However, even with the numerous benefits of biodiesel, certain limitations remain, such as increased emissions

of nitrogen oxides and the need for consistent feedstock quality (Chozhavendhan et al., 2020). Efforts to overcome these challenges have led researchers to explore fuel blends combining biodiesel with petroleum fuels or additives to improve performance, reduce emissions, and optimize combustion characteristics (Wan Osman et al., 2024).

Blending allows for the gradual integration of renewable fuels into the existing energy system without requiring significant modifications to diesel engines or infrastructure (Akhihiero, 2022; Supriyanto et al., 2021). According to Supriyanto et al. (2021), blends like B5 and B20 provide flexibility by adjusting the biodiesel proportion in the fuel, enabling a smoother transition from fossil fuels. Blending also enhances combustion efficiency, reduces engine deposits, and can improve overall fuel quality. Moreover, it offers a cost-effective alternative during fluctuations in fossil fuel prices, making it a practical and economically viable strategy for promoting cleaner energy use (Akhihiero, 2022; Supriyanto et al., 2021).

Therefore, it is important to explore the performance characteristics of a petrol and waste vegetable oil blend in a compression ignition engine. While petrol is traditionally associated with spark-ignition engines, its inclusion in small proportions with biodiesel can help to lower the viscosity of the blend, improve volatility, enhance atomization during injection, and potentially lead to better combustion efficiency in compression ignition engines (Supriyanto et al., 2021). This innovative blend could reduce cold start issues, improve ignition delay, and balance the combustion process while still leveraging the environmental benefits of biodiesel (Wan Osman et al., 2024). Research into such hybrid fuel blends is essential as nations and industries seek transitional solutions toward a low-carbon future. Instead of fully switching to electrification or hydrogen-based systems, which require significant investments and infrastructure, the use of

optimized fuel blends provides a realistic and cost-effective pathway, especially in resource-limited settings (Supriyanto et al., 2021).

## 1.2. PROBLEM STATEMENT

The global energy sector continues to face critical challenges driven by environmental degradation, the depletion of fossil fuel reserves, and rising fuel prices. In developing nations like Nigeria, the reliance on imported diesel not only exerts economic pressure but also exposes the country to supply instability. At the same time, waste vegetable oils are generated in large quantities from household and industrial cooking activities but are often improperly disposed of, leading to environmental pollution and blocked drainage systems.

Biodiesel derived from waste vegetable oil presents a renewable and environmentally friendly alternative to fossil diesel. However, its direct use in diesel engines is often limited by high viscosity, low volatility, and poor cold-start performance. Blending waste vegetable oil with petrol has been proposed as a means of improving fuel properties to meet the requirements of compression ignition engines. Despite this potential, there is limited research on the performance evaluation of such blends, particularly a 20 percent petrol and 80 percent waste vegetable oil mixture, using laboratory-based characterization and comparative literature analysis. The high cost, technical demands, and infrastructure required for live engine testing limit the feasibility of such experiments in many research settings. This creates a knowledge gap in assessing alternative fuels using practical, cost-effective approaches that do not require direct engine testing. Without such studies, the promotion and adoption of waste-based fuel blends remain uncertain and unsupported.

## 1.3. AIM AND OBJECTIVES

### 1.3.1. Aim:

To investigate the performance characteristics of 20% biodiesel and 80% petrol diesel blend in a compression ignition engine.

### 1.3.2. Objectives:

i. To collect, pre-treat waste vegetable oil for fuel blending.

ii. To blend 20% biodiesel and 80% petrol diesel by volume.

iii. To characterize the fuel blend based on parameters such as viscosity, density, flash point, calorific value, and cetane number.

iv. To compare the results with established biodiesel standards and published experimental data on similar blends.

v. To evaluate the blend's potential for use in compression ignition engines.

## 1.4 SCOPE OF STUDY

This study focuses on the preparation and characterization of a 20:80 biodiesel–petrol diesel blend. The research involves laboratory-based analyses, including physicochemical testing of the blend in compression ignition engine. The blend will be assessed using parameters relevant to compression ignition engines, and conclusions will be drawn based on comparisons with accepted standards and past studies.

## 1.5. SIGNIFICANCE OF STUDY

This study holds both scientific and socio-economic significance. Environmentally, it contributes to the global pursuit of clean and renewable energy by exploring the reuse of waste vegetable oil as an alternative fuel. By converting a common environmental pollutant into a valuable resource,

the study promotes waste management and resource efficiency. Economically, it supports local fuel independence by proposing a cost-effective blend that can reduce reliance on imported diesel. From a technical standpoint, the study provides a detailed physicochemical characterization of a novel fuel blend using accessible laboratory procedures. This offers a practical alternative for institutions and researchers who may lack access to engine testing facilities but still wish to assess the viability of alternative fuels. Additionally, by comparing the results to documented engine-based studies, the research bridges the gap between laboratory analysis and real-world engine performance. Ultimately, the study supports broader goals in chemical engineering, energy innovation, and environmental policy by presenting evidence-based insights into the potential of blending waste vegetable oil with petrol. It may inform future research, industrial applications, and sustainable energy strategies, especially in developing regions.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1. ENERGY: RENEWABLE AND NON-RENEWABLE SOURCES

The crucial element underlying economic advancement is energy, serving as a fundamental motor in sustaining contemporary economies and society (Oyedepo et al., 2019). The trajectory of our future economic advancement rests heavily upon the sustained, continuous accessibility of energy obtained from sources that are not only easily available but also secure as well as cost-effective (Jaiswal et al., 2022). A crucial aspect of this is the recognition that the global economy has witnessed a substantial surge in energy demand (Irena, 2022). Projections indicate an anticipated 84 percent increase in energy consumption by 2035, especially within the developing nations (Ahmad & Zhang, 2020). This surge underscores the growing importance of securing energy resources to meet the evolving needs of expanding economies, emphasizing the imperative for accessibility, safety, and affordability in energy sources to foster sustained global economic growth (Oyedepo et al., 2019). Also, while renewable energy sources can be replenished naturally over time and are not depleted when used, non-renewable energy, which is derived from finite resources that cannot restore themselves over a short period and diminishes over time. Renewable energy sources are considered sustainable and environmentally friendly, while non-renewable energy is not considered sustainable in the long term due to the extended time required for its formation (Flórez-Orrego et al., 2015; Güney, 2019).

Renewable energy adheres to the tenets of environmental sustainability by providing a cleaner and more enduring alternative to non-renewable sources. Unlike non-renewable sources that lead to environmental degradation and are finite, renewable energy sources offer a sustainable solution (Kabeyi & Olanrewaju, 2022).

## 2.2. SUSTAINABLE DEVELOPMENT GOALS (SDGs) AND ENERGY EFFICIENCY

Energy is a critical component that drives the Sustainable Development Goals (SDGs) and affects many aspects of human life, including economic prosperity, agricultural output, general well-being, education, gender parity, empowerment, access to clean water, sanitation, and employment opportunities (Santika et al., 2019). Energy also plays a pivotal role in reshaping economies and societies. Although the Sustainable Development Goals (SDGs) are globally applicable goals, they are typically implemented within national and local frameworks, which have a notable impact on the energy landscape. Energy dynamics will unavoidably be impacted by the SDGs' incorporation into regional and national development plans (Santika et al., 2019). Specifically, using more energy will be required to solve issues with poverty reduction, hunger elimination, health enhancement, education advancement, gender equity, and the provision of clean water and electricity as well as the achievement of other SDGs. Research validates the complex relationship between energy requirements and achieving sustainable development goals (Santika et al., 2019).

Concerns have been raised by the recent increase in CO2 emissions and energy use. Anwar et al. (2020) and Osobajo et al. (2020) credit this tendency to the growing urban population (Anwar et al., 2020; Osobajo et al., 2020), while Zakari et al. (2022) speculate that the production of products and services may play a role. Whatever the reason, the utilization of energy has emerged as a critical component of sustainable development. According to projections, the world's industrial energy consumption could increase by almost 30% by 2050 (Yu et al., 2022). The consumption of final products is expected to surpass 310 quadrillion BTUs. The aforementioned rise in energy use is expected to have implications for the economic, societal,

and environmental domains. Thus, in order to reduce CO2 emissions, governments and policymakers need to give priority to implementing cleaner energy options (Zakari et al., 2022).

Aim 7 promotes universal access to affordable, clean energy by supporting renewable energy sources, including wind and solar energy. In line with the SDGs' objectives for eradicating poverty, promoting health, and protecting the environment, renewable energy integration promotes economic growth, environmental sustainability, and social well-being (McCollum, 2018). In order to achieve SDG 7, which is to ensure that everyone has universal access to affordable, dependable, sustainable, and modern energy, renewable energy is essential. By lowering greenhouse gas emissions, it combats climate change (SDG 13) and fosters economic growth (SDG 8) through employment creation (Santika et al., 2019). The 17 Sustainable Development Goals (SDGs) include gender equality, health, education, clean water, and peace in addition to the eradication of poverty. These objectives are met by renewable energy, which promotes sustainable development while reducing the effects of climate change (Gielen et al., 2019).

### 2.3. BIODIESEL AS A SUITABLE RENEWABLE ENERGY

Over the last twenty years, biodiesel has developed as a compelling alternative to fossil fuels, establishing itself as a realistic replacement for petrodiesel due to its similar qualities (Nath et al., 2019). Biodiesel has various advantages over regular petrodiesel, including decreased viscosity, a higher flash point, an enhanced cetane number, good lubricating characteristics, biodegradability, non-toxicity, and a lowered greenhouse gas emission profile. Furthermore, biodiesel boasts a reduced ignition delay time and excellent combustion efficiency, which contribute to lengthening engine life (Manigandan, Atabani, et al., 2020; Manigandan, Gunasekar, et al., 2020; Manigandan, Sarweswaran, et al., 2020; Wakil et al., 2015). This

adaptable fuel can be used directly in diesel engines or combined with petrodiesel with few changes necessary. As a result, biodiesel has attracted the attention of the scientific community, motivating various researchers to study its potential and work towards establishing its sustainability for wider application (Brahma et al., 2022).

Choosing biodiesel as an alternative fuel has several benefits over fossil fuels, particularly in its adaptability for diesel engines. Its low carbon content makes it a possible alternative to heating oil. Biodiesel aids in the carbon cycle, preventing the release of stored carbon into the atmosphere (Brahma et al., 2022). Formed from fundamental elements-sunlight and carbon dioxide – biodiesel shows a favourable energy balance, which is the ratio of energy stored in the fuel to the energy needed for growth, processing, and distribution. With an energy balance ratio surpassing 2.5 to 1, biodiesel successfully collects solar energy (Tile et al., 2017).

In the pursuit of alternative fuels, considerations of renewability, environmental friendliness, cost-effectiveness, and sustainability are paramount and hinge on the availability and cost of feedstocks. A diverse array of oil feedstocks, including soybean, sunflower, palm, jatropha, pongamia, yellow oleander, castor, neem, rubber, as well as animal fat, microalgae lipid, sewage sludge, and waste cooking oil (WCO), contribute to biodiesel production (Brahma et al., 2022). Global biodiesel production, as reported by the USDA-Biofuels Annual Reports 2015, predominantly features soybean oil (30%), rapeseed oil (25%), palm oil (18%), oils from other vegetable seeds (11%), WCO (10%), and fat (6%) (Naylor & Higgins, 2017).

Criticism has arisen due to the scarcity of edible oils, prompting a shift towards non-edible oil sources, used cooking oils, and by-products from the edible oil industry as potential feedstocks. Non-edible second-generation oils like jatropha, pongamia, mahua, and yellow oleander are considered viable due to their renewability, biodegradability, and non-toxicity. However, these

sources necessitate significant land cultivation for sustainability (Rezania et al., 2019a). The third-generation oil from microalgae is in early development stages, requiring additional efforts for global cultivation and availability as a biodiesel feedstock (S. Kumar et al., 2021). Additionally, waste oils, oils from microalgae, animal fats, and byproducts of oil industries are available but in limited quantities (Brahma et al., 2022).

### 2.3.1. Historical Background of Biodiesel

The publication of "The Theory and Construction of a Rational Heat Engine" by German inventor Dr. Rudolph Diesel in 1893 marked a pivotal moment in the development of the diesel engine. Vegetable oil was initially utilized when Rudolph Diesel successfully operated the first diesel engine on peanut oil at the 1900 World's Exhibition in Paris (Rathore et al., 2019). Oilseed crops were the main source of the huge growth in biodiesel output. Diesel engines were commonly powered by vegetable oils until the 1920s. The advantages of vegetable oils, including profitability, availability, low sulfur and aromatic content, biodegradability, and renewability, positioned them as superior to diesel fuel (Oyedepo et al., 2019). However, the current higher market values and challenging applications have limited the widespread use of crops for biodiesel production.

### 2.3.2. Importance of Biodiesel as a Renewable Fuel

Petro-diesel's qualities are mirrored in biodiesel, which is a refined fuel derived from organic sources (Hazrat et al., 2020). Serving as a secure substitute for traditional petroleum fuel, biodiesel stands out as an eco-friendly solution. This environmentally sensitive fuel provides clean combustion and offers high lubricity. Originating from renewable sources, biodiesel emulates the performance of petroleum diesel while dramatically lowering air pollution. Its biodegradable nature matches with eco-friendly methods, reinforcing its safety for the

environment (Rathore et al., 2019). The creation of biodiesel involves numerous processes, providing flexibility in manufacturing. According to Jamil et al. (2021), this fuel is a monoalkyl ester of fatty acids obtained from animal fat, edible and non-edible vegetable oils, and other biofuels such as ethanol and methanol (Jamil et al., 2021). Thus, using biodiesel offers a feasible option for conventional diesel fuels derived from petroleum, encouraging ecologically friendly and sustainable energy practices.

Due to the rising depletion of fossil fuels and their bad influences on the environment, investigations on the use of renewable energy resources as an alternative fuel for engines are underway (Jagtap et al., 2020; Passaponti et al., 2019; Simsek, 2020; Simsek & Uslu, 2020b; Sun et al., 2020; Xiao et al., 2020; Yesilyurt, 2020a). The employment of biodiesel as an alternative fuel in compression ignition engines has been in considerable demand for years owing to its chemical properties near to diesel (M. Aydın et al., 2020; Şimşek et al., 2020; Venu et al., 2019). Biodiesel is a diesel engine fuel alternative that may be generated from animal or vegetable oils (Simsek & Uslu, 2020c). Animal waste oils may be divided into themselves as chicken oil, fish oil, ovine and bovine oils, and vegetable oils as rapeseed oil, canola, cotton oil, and safflower (Krishania et al., 2020; Yesilyurt et al., 2020). Biodiesel, which may be made from animal, vegetable, and waste oils by different techniques, can be utilized in diesel engines in pure form or by blending it in a specified ratio (S. Aydın, 2020; M. Singh & Sandhu, 2020).

Biodiesel provides numerous benefits compared to diesel fuel in terms of fuel attributes (Simsek & Ozdalyan, 2018; Yesilyurt, 2020b). Biodiesel is preferable to diesel fuel with its high cetane number, fewer hazardous exhaust emissions, lubricant features, flash point, and inexpensive cost of acquiring (Elkelawy et al., 2019, 2020; Gharehghani & Pourrahmani, 2019; Heidari-Maleni et al., 2020; Uslu & Aydın, 2020; Yesilyurt, 2020b). Since animal fats are damaging to human

health, they are better suited to be employed in alternative fields such as fuel than in the food business (Simsek & Uslu, 2020a). Because animal oils are solid and relatively viscous at room temperature, they have restricted their usage as fuel in diesel engines. Animal oils produce low pressure, poor combustion, low vapor-air mixture, low atomization, and buildup of hazardous compounds in the engine. Micro-emulsion, dilution, pyrolysis, and transesterification procedures are used to enhance the viscosity and physical qualities of vegetable and animal oils. The most extensively utilized among these procedures is the transesterification process (Simsek & Uslu, 2020a).

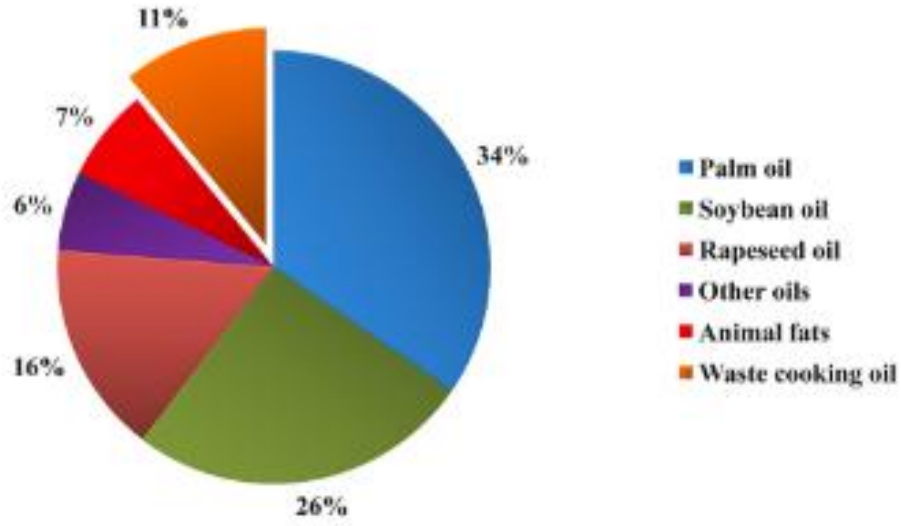


*Figure 2- 1: Percentage share of different oils in biodiesel production (Singh et al., 2021)*

## 2.4. METHODS OF BIODIESEL SYNTHESIS

Since the invention of the diesel engine and Dr. Rudolf Diesel's utilization of vegetable oil as fuel, the continuous development of biofuels, particularly biodiesel, has been acknowledged (Owolabi et al., 2012). Numerous researchers have undertaken significant efforts to advance biodiesel production methods, aiming to optimize product yields, enhance fuel properties, and reduce production costs. Vegetable oils, characterized by high viscosity and low stability against

oxidation, present challenges in their direct use as fuels. To address these issues, four distinct approaches have been explored for converting oils into biodiesel: dilution, micro-emulsification, pyrolysis, and transesterification (Robles-Medina et al., 2009). Researchers have diversified these methods to create sustainable biodiesel solutions, taking into account the economic feasibility of large-scale production. The ongoing investigations reflect the commitment to refining biodiesel processes for broader applicability and environmental benefits.

### 2.4.1. Dilution Method

This approach involves mixing vegetable or animal oils with petrol diesel in the range of 10 to 40% (w/w) for use as fuel in diesel engines (Rezania et al., 2019a). Existing literature documents successful blending of vegetable oils with diesel, including notable instances during World War II by Nye et al (Nye et al., 1983). Caterpillar Brazil Company demonstrated effective power maintenance using a 10% vegetable oil blend with diesel in the pre-combustion chamber in 1980, requiring no engine modifications. Successful results were reported for a 20:80 ratio of vegetable oil to diesel, as well as a 5% diesel and 95% used cooking oil mixture in 1982 (Ramadhas et al., 2004). Pramanik et al (2004) successfully operated an engine using a 50% blend of Jatropha curcas oil without significant operational challenges (Ramadhas et al., 2004). Following multiple research attempts, a discussion on the development, methodology, and limitations of using vegetable oil as fuel took place in August 1982 at the Fargo, North Dakota conference (Misra & Murthy, 2010; Owolabi et al., 2012). However, blending is suitable only for liquid and portable diesel fuels with approximately 80% heat content. It is not suitable for oils with higher viscosity, a high unsaturated carbon chain, and low volatility. Using 100% vegetable oil in engines raises issues like coking, trumpet formation, carbon deposition, oil ring sticking, thickening, and gelling of lubricating oil. The exploration of a generalized technology to economically produce

biodiesel, addressing these challenges, is emphasized as an alternative fuel for the future (Leung et al., 2010; Ramadhas et al., 2004).

### 2.4.2. Micro-emulsification

Micro-emulsification is the process of dissolving vegetable or animal oils in alcoholic solvents and surfactants. To address the issue of high viscosity in vegetable oils, micro-emulsions are formed using various alcoholic solvents, such as methanol, ethanol, butanol, and hexanol, resulting in colloidal microstructures ranging from 1 to 150 nm (Rezania et al., 2019b). These micro-emulsions are transparent, optically isotropic, clear, and stable colloidal dispersions with dispersed phase droplets or particles having diameters between 100 and 1000 Å. The dispersion components include surfactant, water, oil, and a small co-surfactant molecule.

Despite having lower heating values than diesel fuels due to high alcohol content, micro-emulsions play a role in reducing nozzle coking by leveraging the alcohols' high latent heat of vaporization, cooling the combustion chamber. A specific case demonstrated the reduction of viscosity to 11.2 $mm^2/s$ at 25°C by using 2-octanol as an amphiphile in the micellar solubilization of methanol in triolin with soybean oil (Yusuf et al., 2011). However, challenges such as carbon accumulation around injector nozzle tubes and valves were reported when using a micro-emulsification fuel composed of oil, methanol, 2-octanol, and cetane improver in a specific ratio (Srivastava & Prasad, 2000). This micro-emulsification fuel, having a low cetane number, may lead to incomplete combustion (Leung et al., 2010). Therefore, there is a pressing need for an advanced biodiesel conversion procedure in addition to utilizing micro-emulsification, especially in the biorefinery sector.

### 2.4.3. Pyrolysis

The process of producing biodiesel through pyrolysis involves heating vegetable oil, animal fats, triglycerides, or fatty acid components at elevated temperatures (300-1300°C) without the presence of oxygen or air. This method induces a transformation in the structure of long-chain and saturated compounds, leading to the cleavage of chemical bonds and the formation of smaller molecules. Thermal cracking can occur with or without the assistance of a catalyst. The thermal decomposition of vegetable oil results in the production of alkanes, alkadienes, aromatics, alkenes, carboxylic acids, and small amounts of gaseous by-products. Pyrolysis is categorized based on the temperature range into conventional pyrolysis (550-900 K), fast pyrolysis (850-1250 K), and flash pyrolysis (1050-1300 K) (Balat, 2007; Karmakar & Halder, 2019; Mishra & Goswami, 2018). It is considered a straightforward, highly efficient, waste-free, and eco-friendly process. Biodiesel generated through pyrolysis exhibits favorable fuel properties, including low viscosity, high cetane number, acceptable copper corrosion rate, and concentrations of sulfur, with water and sediment content within limits. However, undesirable aspects include high ash content, carbon residues, and pour points of the resulting product (Atabani et al., 2012). The substantial energy requirement for pyrolysis and associated limitations prompt the scientific community to explore more cost-effective techniques for biodiesel production.

### 2.4.4. Transesterification

As per the American Society for Testing and Materials (ASTM), biodiesel is described as a blend of alkyl esters derived from long-chain fatty acids through the transesterification of triglycerides (Changmai et al., 2020; Manchuri et al., 2018). Transesterification, a highly convenient method for biodiesel production, involves converting vegetable oil or any triacylglycerol with alcohol in

the presence of a catalyst, resulting in the formation of alkyl esters (biodiesel) and glycerol (Akhihiero, 2022; Rezania et al., 2019b). The reaction necessitates a stoichiometric 3:1 alcohol-to-oil ratio (ATOR) for completion, and it is reversible, requiring an excess of alcohol to favor the production of the desired products.

Commonly employed alcohols in transesterification for biodiesel synthesis include methanol, ethanol, propanol, butanol, and amyl alcohol. Methanol is the preferred choice due to its cost-effectiveness, polarity, and shorter chain length. Various catalysts used in biodiesel synthesis encompass homogeneous acids and bases, enzymes, and heterogeneous solid acids and bases (Brahma et al., 2022). Base-catalyzed transesterification is approximately 4000 times faster than acid-catalyzed transesterification. Key factors influencing the reaction include ATOR, reaction temperature, the type of catalyst used, and its load percentage (Mishra & Goswami, 2018; Nath et al., 2019). Transesterification is widely regarded as the most preferred method by researchers for biodiesel synthesis, resulting in biodiesel meeting the fuel property standards of EN 14214 and ASTM D6751. Despite its advantages, the notable drawback of transesterification is the requirement for excess methanol (Leung et al., 2010). Consequently, the pursuit of optimal conditions for transesterification, along with the development of efficient, cost-effective, and environmentally friendly catalysts, remains a central concern for large-scale biodiesel production.

## 2.5. PURIFICATION OF BIODIESEL

The purification of biodiesel is crucial to remove impurities such as free glycerol, soap, excess alcohol, residual catalysts, and other contaminants. These impurities not only affect engine performance but also complicate handling and storage. Purification ensures compliance with quality standards like ASTM D6751, reducing water content to below 500 ppm. Also, purification enhances fuel quality, improving combustion efficiency and reducing harmful

emissions (Atadashi, Aroua, & Aziz, 2011; Banga & Varshney, 2010). This process is vital for producing biodiesel that meets stringent performance and environmental criteria, ensuring optimal engine operation and minimizing negative impacts on health and the environment (Maheshwari et al., 2022). Various methods are employed for this purpose. Some commonly employed method include:

### 2.5.1. Wet or Water Washing

The wet washing technique is conventionally employed to eliminate various impurities such as unreacted oil, surplus catalyst, alcohol, salts, soaps, and organic contaminants from raw biodiesel. During wet washing, water serves as the purifying agent, capable of incorporating acid to neutralize any remaining alkali catalyst. This method facilitates the removal of salt byproducts resulting from the transesterification process. It's imperative to eliminate excess alcohol post-transesterification to minimize its presence in residual wastewater (Gokhan Demir & Soyhan, 2017). Some researchers advocate for the removal of excess alcohol following wet washing. They achieved this by employing distilled water at approximately 50-60°C to prevent the precipitation of saturated fatty acid esters. Gentle water washing promotes rapid and complete phase separation, reducing emulsion formation. The utilization of hot distilled water yields biodiesel with a purity of 99%. While both dry and wet washing methods are utilized in commercial biodiesel production, it is argued that only the wet washing process can sufficiently purify biodiesel to meet EN14214 standards (Gokhan Demir & Soyhan, 2017).

In addition to its benefits, wet washing exhibits certain disadvantages, including prolonged separation duration and reduced product yield. The leakage of biodiesel into the rinsing water contributes to heightened pollution in the effluent, exacerbating environmental concerns.

Moreover, the substantial volume of wastewater generated during wet washing poses significant challenges for both the biofuel sector and the ecosystem (Catarino et al., 2020).

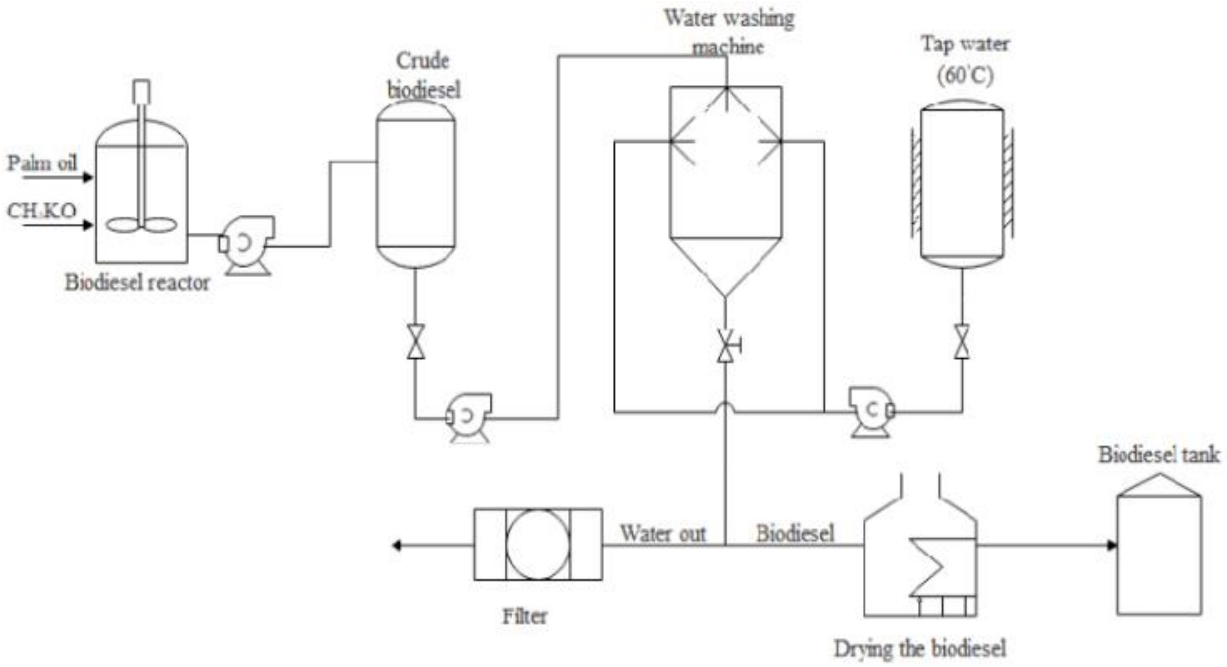


*Figure 2- 2: General scheme of the proposed biodiesel production process with an emphasis on biodiesel wash-water reuse.*

### 2.5.2. Dry Washing

Dry washing stands out as a frequently utilized method in the biodiesel purification process. It employs various adsorbents like Amberlite, Purolite, cellulosics, Magnesol, Trisyl, activated carbon, activated fiber, and activated clay. These adsorbents contain sites for both acidic and basic adsorption, effectively attracting polar substances such as glycerol and methanol (Atadashi, 2015). Enhancing efficiency, a filter unit, depicted in Figure 1, is incorporated. Operating at 65°C, the process concludes within 20–30 minutes (Leung et al., 2010). Dry washing significantly reduces glycerides and total glycerol levels, resulting in a waterless procedure that enhances fuel quality. Additionally, it simplifies integration into existing plants, reduces washing time, eliminates waste-water production, minimizes total surface area coverage of the wash tank,

and saves space (Atadashi, 2015). Research indicates that this method decreases production costs and time, thereby optimizing the refining of crude biodiesel. The biodiesel refinement process yields high-quality fuel without the addition of water, increasing the likelihood of achieving a water content below 500 ppm, as mandated by ASTM D6751. Comparatively, water washing methods often result in fuel water content exceeding 1000 ppm, making water removal arduous and expensive (Atadashi, 2015). Additionally, biodiesel derived from waste frying oil underwent refinement using rice husk ash (RHA) at various concentrations (1-5% w/w), alongside commercial adsorbent MagnesolÒ 1% (w/w) and conventional acid solution (1% aqueous H3PO4). RHA, particularly at a 4% concentration, exhibited exceptional efficacy in purging impurities from biodiesel due to its high silica concentration and the presence of meso and macropores. Consequently, rice husk ash, a by-product of rice processing, emerges as a viable substitute material for crude biodiesel refinement.

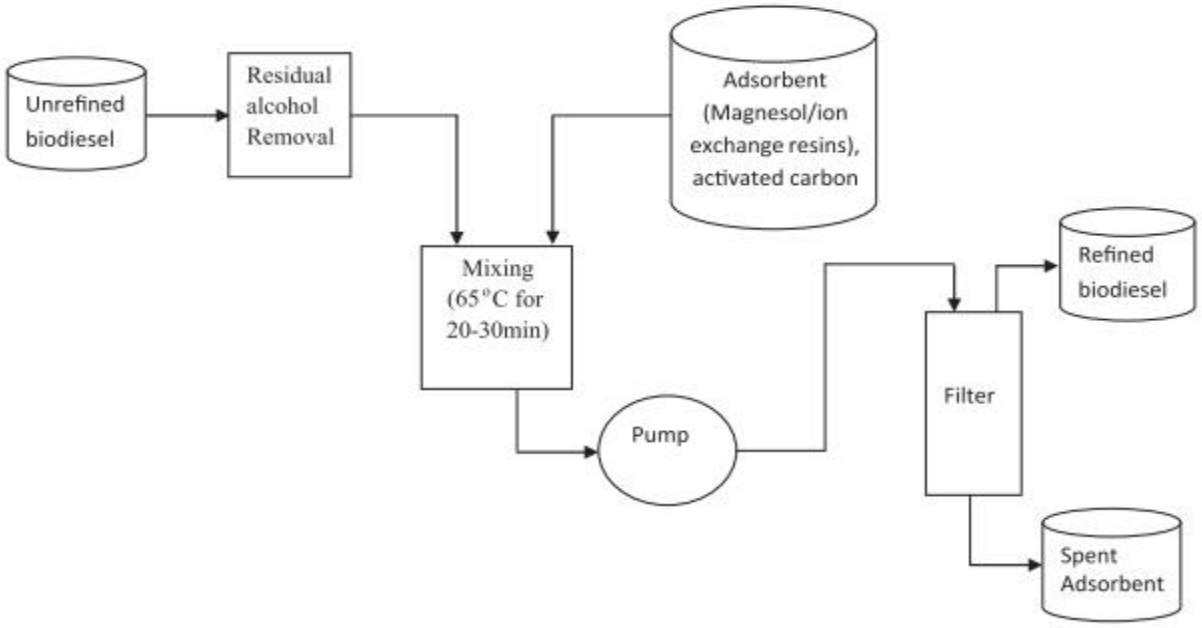


*Figure 2- 3: Schematic diagram of biodiesel dry washing technology*

### 2.5.3. Membrane Extraction

Membranes serve as semi-permeable barriers that delineate various species within a solution by permitting the selective passage of specific components. These membranes can exhibit diverse characteristics, such as homogeneity or heterogeneity, symmetry or asymmetry, solid or liquid composition, and varying electrical charge. Transport across membranes can be influenced by convection or molecular diffusion, prompted by factors like electric fields, concentration gradients, pressure differentials, or temperature variations. While membrane-based separations are widely used in water purification, protein isolation, and gas separation, their commercial applications are mostly confined to aqueous solutions and inert gases, with the treatment of non-aqueous fluids representing an emerging frontier (Aziz, et al., 2011).

Membrane extraction is an effective method for purifying biodiesel, offering promising results in enhancing the quality of biodiesel fuel. It involves the use of membranes as semi-permeable barriers to selectively separate components within a solution (Atadashi, 2015). Recent studies have shown that membrane extraction can produce high-quality biodiesel with reduced impurities, contributing to improved engine performance (Atadashi, 2015). This environmentally friendly technique is gaining attention as a novel method for biodiesel purification, alongside other emerging technologies like extraction by ionic liquids or deep eutectic solvents (Ostojcic et al., 2020). Membrane processes offer a viable approach to both biodiesel production and purification, addressing the need for efficient and sustainable fuel production methods (Reis & Cardoso, 2016). The efficiency of membrane separation hinges on various factors including membrane composition, operational pressure, temperature, flow velocity, and interactions between feed components and membrane surfaces (Aziz, et al., 2011).

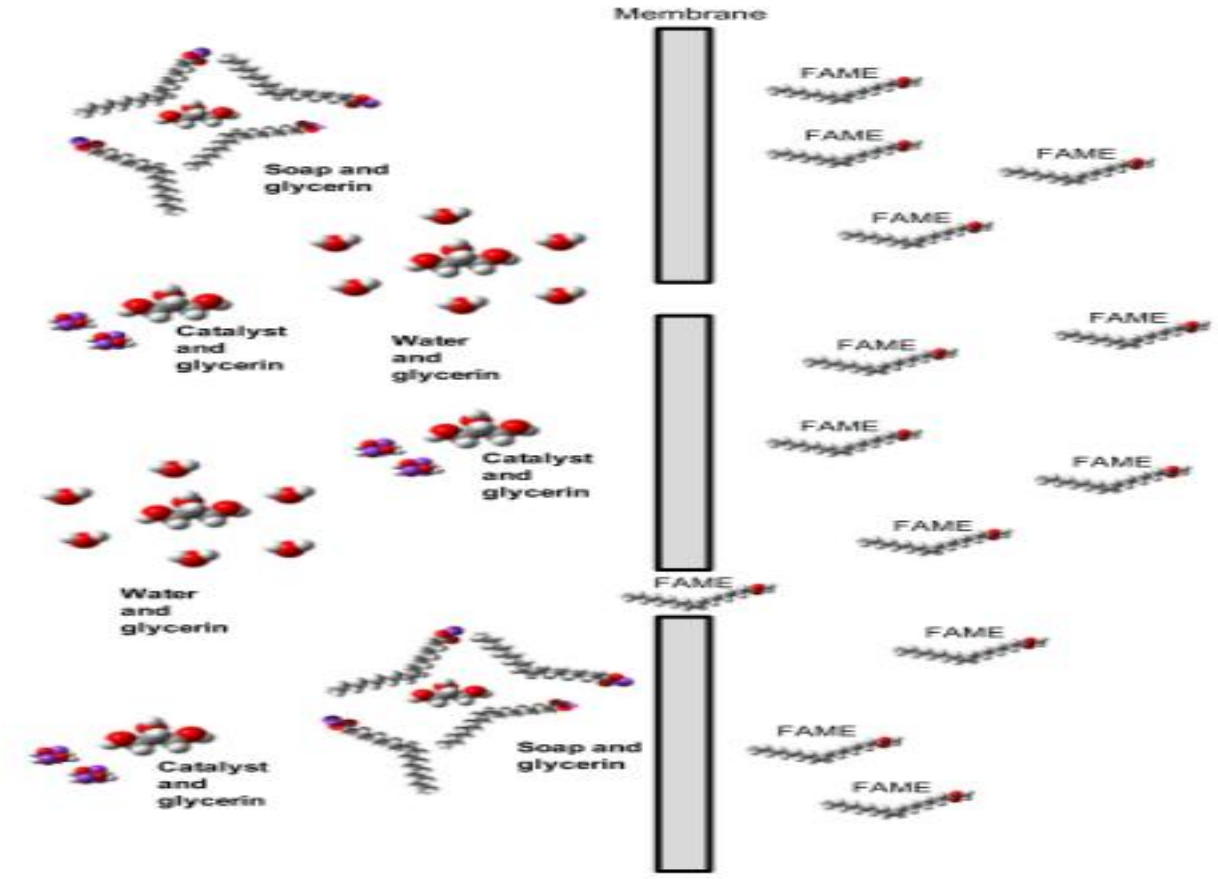


*Figure 2- 4: Separation mechanism of biodiesel impurities by membrane.*

## 2.6. PROPERTIES OF BIODIESEL

For the production of biodiesel, often referred to as fatty acid methyl esters (FAME), triacylglycerol and other molecules, along with vegetable and animal fats, can be utilized (Sujin et al., 2024). FAME is a product of the metabolism of methanol. But a fatty ester's overall characteristics are shaped by the interaction between the fatty acid chain and the alcohol group (Yu et al., 2022). For the purpose of producing fatty acid alkyl esters (FAAE) for biodiesel synthesis, the characteristics modified by alternative alcohols are therefore worthy of evaluation. Among the important characteristics that are being discussed are lubricity, kinematic viscosity, cetane number (CN), cold flow, and oxidative stability (Knothe, 2016).

### 2.6.1. Cetane Number and Combustion

Cetane Number (CN) acts as a critical measure of diesel fuel (DF) quality, reflecting its igniting behavior. Higher CN levels correspond with shorter ignition delay durations, indicating quick ignition upon injection into the cylinder. Standards like ASTM D613 and ISO 5165 guide CN determination globally (Kim et al., 2023). Hexadecane, with a CN of 100, sets the high-quality benchmark, while 2,2,4,4,6,8,8-heptamethylnonane (HMN) at CN 15 reflects low ignition quality due to greater branching and reduced chain length. CN diminishes with shorter chains and increased branching. Petrodiesel standards necessitate a CN minimum of 40, whereas biodiesel requires 47 (ASTM D6751) or 51 (EN 14214). The old CN determination method involves extensive fuel utilization, leading to the invention of the Ignition Quality Tester™ (IQT™). It offers a derived cetane number (DCN) corresponding to traditional CNs. DCN values of less saturated compounds exhibit higher consistency in the literature due to the nonlinear connection between CN and ignition delay time (Guan et al., 2019). Despite greater CNs of fatty molecules, biodiesel operation generally increases NOx emissions. The CN's intricate relationship with engine emissions encompasses elements including injection pressure and combustion temperature. CN study of biodiesel, initially conducted with palm oil ethyl esters, indicated a relationship between compound structure and CN, exhibiting CN decrease with increased unsaturation and chain length. Branched esters give superior low-temperature characteristics. The CN of biodiesel blends can be determined using a summation equation, with chain length determining heat of combustion (HG), an important feature for diesel fuels (Knothe, 2016).

$$CN_{mix} = \sum A_c \times CN_c \qquad (2.1)$$

The notation "$CN_{mix}$" symbolizes the Cetane Number (CN) that defines the biodiesel mixture, where "Ac" marks the amounts of each constituent, and "CNc" specifies the individual Cetane Number of each component in the blend (Knothe & Steidley, 2011).

### 2.6.2. Oxidative Stability

In addition to cold flow difficulties, the oxidative stability of biodiesel is a key concern, especially when kept for a lengthy period of time. The effects of heat, air, metal traces, antioxidants, and peroxides on the oxidation of biodiesel are noted by a number of researchers. Oxidation is catalyzed by components like air, high temperatures, and metals (Knothe, 2016). The Rancimat method, often used to determine oxidative stability, measures conductivity changes during air bubbling at 110°C. Biodiesel standards, including ASTM D6751 and EN 14214, demand minimum oxidative stability times. Oxidative stability is tested using a variety of methodologies, such as pressurized DSC and acid value. The rate of auto-oxidation, which is related with fatty substances, is dependent on the quantity and location of double bonds in the chain. Polyunsaturated fatty acids, such as linoleic and linolenic acids, which are particularly prone to auto-oxidation, have an effect on the oxidative stability of biodiesel (Varghese et al., 2021).

### 2.6.3. Viscosity

Viscosity has a significant impact on engine deposit formation by atomizing fuel during injection into the combustion chamber. Higher viscosity exacerbates these issues, making transesterified oils, such as biodiesel, more prone to atomization challenges and engine deposit formation compared to their parent oils (Ferreira et al., 2021). Neat vegetable oils, with their high viscosity, have been largely abandoned as alternative diesel fuels due to these concerns. Kinematic viscosity, a key parameter, is included in biodiesel standards like ASTM D445 and ISO 3104

(Knothe, 2016). Research has explored the effects of blending petrol diesel and biodiesel on viscosity, resulting in the construction of forecasting models. The length of the chain and the level of fatty material saturation both raise viscosity, including the alcohol moiety (Wang et al., 2019). Factors like double bond orientation effect viscosity, with cis double bonds providing lower viscosity than trans (Dharma et al., 2016). Branching in the ester moiety has negligible influence on viscosity, presenting a possible path for boosting low-temperature qualities without large modifications to other fuel parameters. While dynamic viscosity studies are prevalent, biodiesel standards primarily focus on kinematic viscosity values (Pullen & Saeed, 2014).

In a way analogous to the formula used for estimating the cetane number (CN) of compounds, the kinematic viscosity of a blend of fatty esters can be determined using the equation put forward by Knothe and Steidley in 2011 (Knothe & Steidley, 2011).

$$v_{\text{mix}} = \sum A_C \times v_C \qquad (2.2)$$

In this case, $v_{mix}$ is the biodiesel sample's kinematic viscosity; $A_c$ is the amount of each individual ester present; and $v_c$ is the kinematic viscosity of each compound in the mixture independently.

### 2.6.4. Lubricity

The emergence of low-sulfur petroleum-derived fuels has underscored the significance of lubricity in diesel fuels (DFs). Conventional petrol diesel desulfurization processes diminish or eliminate its natural lubricity, crucial for the optimal performance of engine components like fuel pumps and injectors (Knothe, 2016). Studies highlight oxygen- and nitrogen-containing compounds as pivotal for petrol diesel's lubricating properties, supported by investigations on specific C-3 compounds. Biodiesel and fatty compounds have demonstrated the ability to

enhance petrol diesel's lubricity, especially in low-sulfur variants, offering an advantage over typical lubricity additives. Free fatty acids, monoacylglycerols, and glycerol display higher lubricating characteristics due to their free hydroxyl (OH) groups, which promote lubricity in fatty acid chains (Silva e Mello et al., 2014). Commercial biodiesel, having components beyond methyl esters, largely promotes petrol diesel lubricity at low mix ratios. Although adding glycerol to plain esters fails to improve petrol diesel lubricity, the introduction of polar molecules such free fatty acids or monoacylglycerols boosts it, underlining their pivotal function in biodiesel-petrol diesel blends (Silva e Mello et al., 2014). However, lubricity testing standards, like ASTM D6079 or ISO 12156, have not yet incorporated lubricity assessments for biodiesel, despite its advantageous performance compared to petrol diesel in this regard (Knothe, 2016).

## 2.7. LIMITATIONS OF ANIMAL-BASED OIL FOR BIODIESEL SYNTHESIS

The effects of biodiesel produced from animal fats obtained by the transesterification method on engine performance and exhaust emissions were examined, and a decrease in engine torque and an increase in BSFC value were observed by adding animal biodiesel into the diesel fuel and in other research, it has been discovered that there is a reduction in emissions such as HC and CO (Simsek & Uslu, 2020a). Krishania et al. (2020) evaluated the applicability of various vegetable and animal biodiesels in compression ignition engines. They carried out their studies at four different engine loads and three different compression ratios. They noted that, in general, plant-based biodiesel delivers superior outcomes in terms of performance and emissions. Rajak & Verma (2018) attempted to minimize emissions by employing five distinct fuels as edible and non-edible plant oil, waste animal oil, waste oil, and alcohol in a single-cylinder compression ignition engine. In basic terms, they said that the greatest results were achieved using animal biodiesel following alcohol. Shahir et al. (2017) evaluated the effects of fuel blends formed by

combining biodiesel derived from animal fat with diesel in various quantities in a Common Rail Direct Injection Engine. Based on their findings, they indicated that the fuel combination containing 30% biodiesel is the test fuel that offers the greatest results in terms of performance and emissions. When the literature studies are investigated, it has been determined that biodiesel derived from waste vegetable oils is commonly utilized, while biodiesel generated from waste animal oils is not favored much (Simsek & Uslu, 2020a).

## 2.8. WASTE COOKING OIL-BASED BIODIESEL AS A RENEWABLE FUEL

Waste vegetable oil-based biodiesel presents a cost-effective and environmentally friendly alternative to conventional diesel, making it a viable retrofit option for use in compression ignition (CI) engines. Biodiesel can be produced from waste cooking oil (WCO) through a transesterification process involving catalysts such as sodium hydroxide, potassium methoxide, sodium methoxide, or potassium hydroxide, resulting in fuel with properties closer to diesel (Das et al., 2018). During repeated frying operations, cooking oils undergo significant physical and chemical degradation, including increased viscosity, density, free fatty acid (FFA) content, and total polar materials (TPM), along with the formation of polymerized triglycerides and a drop in smoke point (Oyedepo et al., 2019). Continued exposure to high temperatures renders the oil unsuitable for cooking, necessitating disposal. Hence, WCO from restaurants and households becomes a valuable feedstock for biodiesel production, reducing waste while providing renewable fuel (Oyedepo et al., 2019).

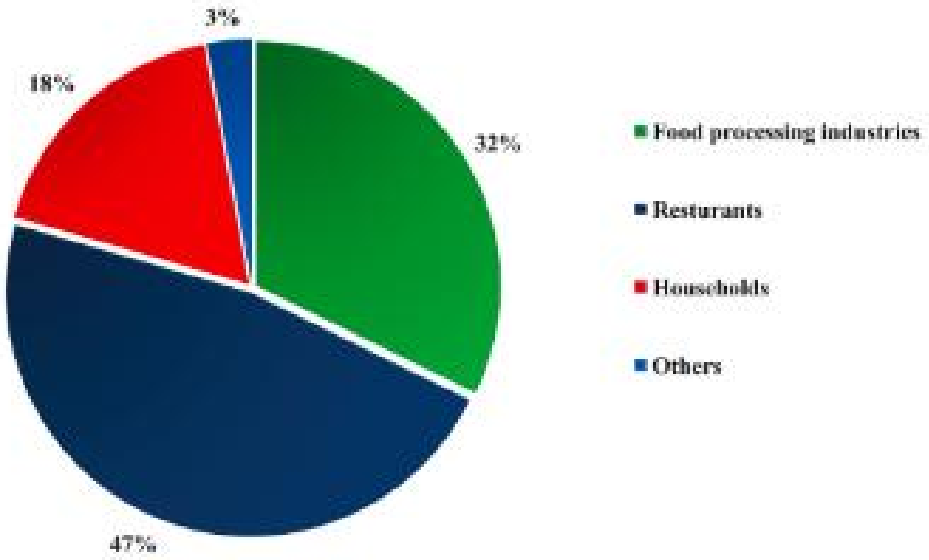


*Figure 2- 5: Sources of WCO generation (Singh et al., 2021).*

However, unmodified vegetable oils present operational and durability challenges when used directly in diesel engines due to their high viscosity and low volatility (Singh et al., 2021). Transesterification addresses these issues effectively, producing lower-viscosity biodiesel suitable for CI engine operation. Studies have demonstrated that waste cooking oil biodiesel performs well in engines operating at 1500 rpm under variable loads, with performance parameters close to conventional diesel fuel (Sander et al., 2018). While the heating value of WCO biodiesel is approximately 15% lower than diesel, exhaust gas temperatures tend to rise with increasing biodiesel concentration due to the oxygenated nature of biodiesel (Abed et al., 2018).

Engine tests using B5 and B10 blends revealed an increase in specific fuel consumption (SFC) by up to 4% and a reduction in thermal efficiency by up to 2.8% compared to pure diesel. Similarly, blends containing 19.6% to 79.6% biodiesel (by volume) showed increased SFC and decreased thermal efficiency as biodiesel proportion increased, confirming that biodiesel's lower

energy content affects overall performance. In a comparative study involving diesel and blends of WCO biodiesel at B5, B20, and B30, the SFC was consistently higher for biodiesel blends due to their lower heating value, while exhaust temperatures were elevated (Abed et al., 2018).

Further experiments using 20%, 40%, 60%, and 80% biodiesel blends in a single-cylinder, water-cooled diesel engine showed that blends resulted in higher exhaust gas temperatures compared to diesel. However, the results suggested that low to medium blend ratios of WCO biodiesel can effectively substitute diesel without significant performance penalties (Abed et al., 2018). The physicochemical characteristics of WCO biodiesel produced via transesterification closely resemble those of diesel, though the increased oxygen content and reduced calorific value contribute to higher SFC and reduced engine thermal efficiency. For example, a 25% blend (B25) demonstrated a 5.69% rise in SFC and lower thermal efficiency compared to diesel when tested under varying loads at a constant engine speed (Abed et al., 2018).

## 2.9. PRE-TREATMENT OF WASTE COOKING BY ESTERIFICATION

The treatment of waste cooking oil (WCO) before transesterification is a critical step in biodiesel production, particularly when the feedstock contains high levels of free fatty acids (FFA) and water. These impurities negatively affect catalyst performance and biodiesel yield, leading to soap formation, emulsion, and reduced ester conversion efficiency (Math & Chandrashekhara, 2016). The esterification process serves as a pretreatment method that converts FFAs in the oil into esters, thereby reducing their concentration to below 1 percent before the main transesterification step (Ambawatte et al., 2020).

Waste cooking oils typically exhibit FFA concentrations greater than 2 percent, arising from oxidative degradation and hydrolysis during repeated heating and frying. These FFAs react with alkaline catalysts to form soaps, which hinder glycerol separation and biodiesel purification (Ge

et al., 2017). To mitigate this, an acid-catalyzed esterification process is employed, using catalysts such as sulfuric acid ($H_2SO_4$), hydrochloric acid (HCl), or p-toluenesulfonic acid. The reaction is generally conducted at moderate temperatures (50 to 65 °C) under reflux conditions, promoting the conversion of FFAs into fatty acid methyl esters (FAMEs) through reaction with methanol (Sujin et al., 2024).

The esterification reaction can be represented as:

$$RCOOH + R'OH \overset{Acid}{\leftrightarrow} RCOOR' + H_2O$$

$$\underset{\text{Triglyceride}}{C_3H_5(OCOR)_3} + \underset{\text{Water}}{H_2O} \leftrightarrow \underset{\text{Diglyceride}}{C_3H_5(OH)(OCOR)_2} + \underset{\text{Ester}}{RCOOH}$$

$$\underset{\text{FFA}}{RCOOH} + \underset{\text{Base}}{NaOH} \leftrightarrow \underset{\text{Soap}}{RCOONa} + H_2O$$

The success of esterification depends on several key parameters, including methanol to oil molar ratio, catalyst concentration, reaction temperature, and mixing intensity. Typically, a molar ratio of 6:1 to 12:1 (methanol to oil) is used to ensure adequate conversion. Excess methanol helps drive the equilibrium toward ester formation and compensates for the water generated during the process (Al Saadi et al., 2020). Reaction times generally range from 60 to 120 minutes, with catalyst concentrations between 0.5 percent and 1 percent by weight of oil. After the reaction, the mixture is allowed to settle into two distinct layers: the upper methyl ester-rich phase and the lower aqueous phase containing residual acid catalyst and water (Salaheldeen et al., 2021).

The upper layer is then washed and dried to remove residual acid and moisture before being subjected to the transesterification process. The effectiveness of the esterification treatment can be evaluated by measuring the acid value or FFA content of the treated oil, which should fall

below 1 mg KOH per gram of oil to ensure compatibility with alkaline catalyzed transesterification (Monika et al., 2023).

Recent studies highlight the advantages of integrating ultrasonic or microwave-assisted esterification, which enhances reaction rates, reduces catalyst dosage, and minimizes methanol consumption (Das et al., 2018; Singh et al., 2021). These advanced techniques also improve process sustainability and economic feasibility by lowering energy demands and reaction time.

Thus, esterification serves as a pivotal step in upgrading waste cooking oil into a suitable feedstock for biodiesel production. It improves process efficiency, reduces soap formation, and ensures high-purity methyl ester yield, making it an essential pretreatment for biodiesel derived from high FFA waste oils.

## 2.10. TRANSESTERIFICATION REACTION

Transesterification has gained widespread acceptance in recent years for converting vegetable oils into products with fuel properties that are more compatible from a technical standpoint. It is a vital process for biodiesel production, crucially reducing the viscosity of feedstock/vegetable oils to levels more akin to conventional fossil-based diesel (Math & Chandrashekhara, 2016). This chemical reaction involves the interchange of the alkoxy moiety, leading to the transformation of one ester into another. Transesterification, typically catalyzed by conventional catalysts like NaOH and KOH, is an equilibrium reaction describing the alcoholysis of carboxylic esters, enhancing ester yields by facilitating equilibrium adjustment (Monika et al., 2023). Vegetable oils are chemically triglyceride molecules with structural variations in their glycerol-bound alkyl moiety. When these triglyceride molecules undergo transesterification with short-chain alcohols and a suitable catalyst, they yield fatty acid methyl esters and glycerol. A

sequence of three consecutive reversible reactions elucidates the overall transesterification process (Mumtaz et al., 2017).

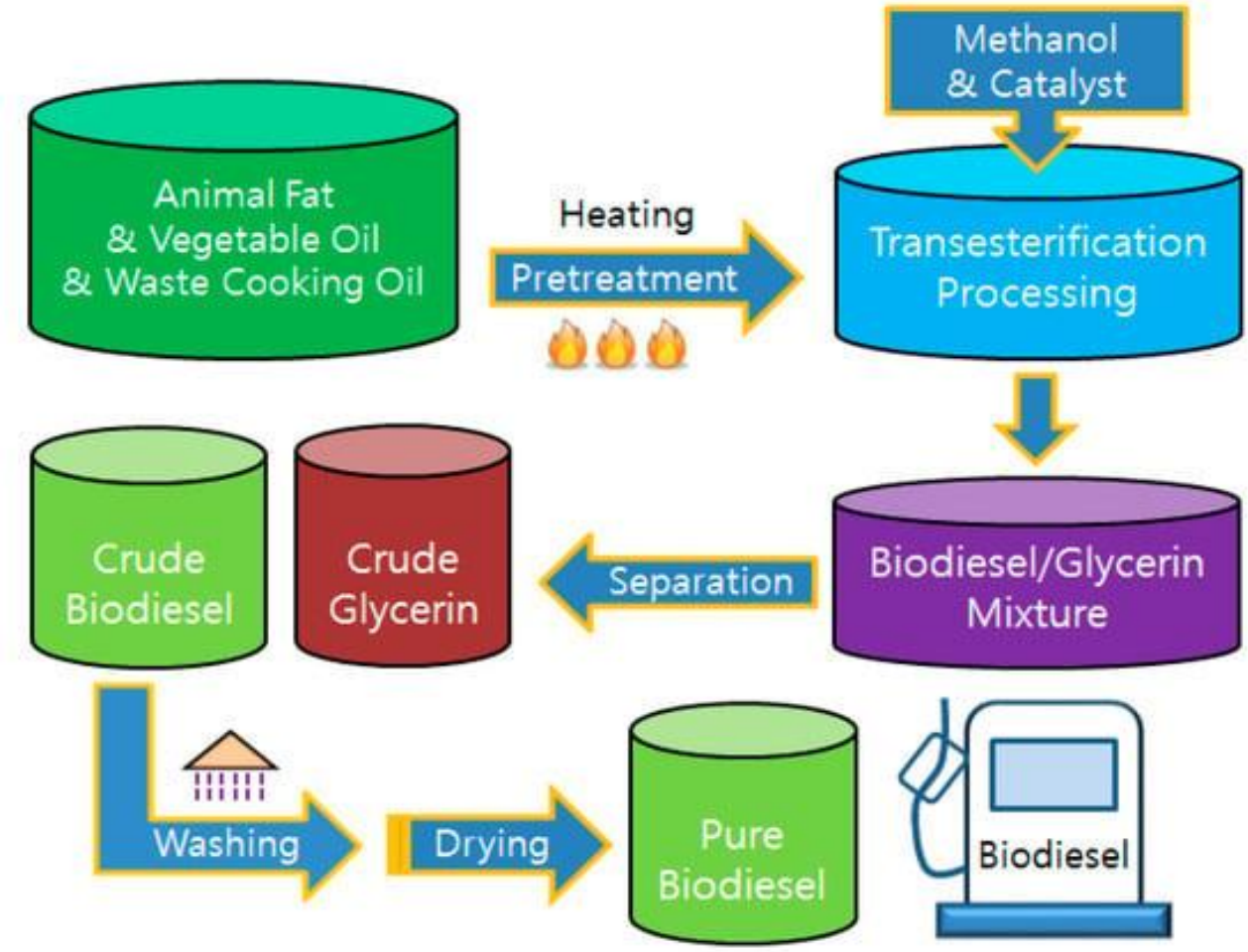


*Figure 2- 6: The specific process of transesterification method for biodiesel production (Ge et al., 2017).*

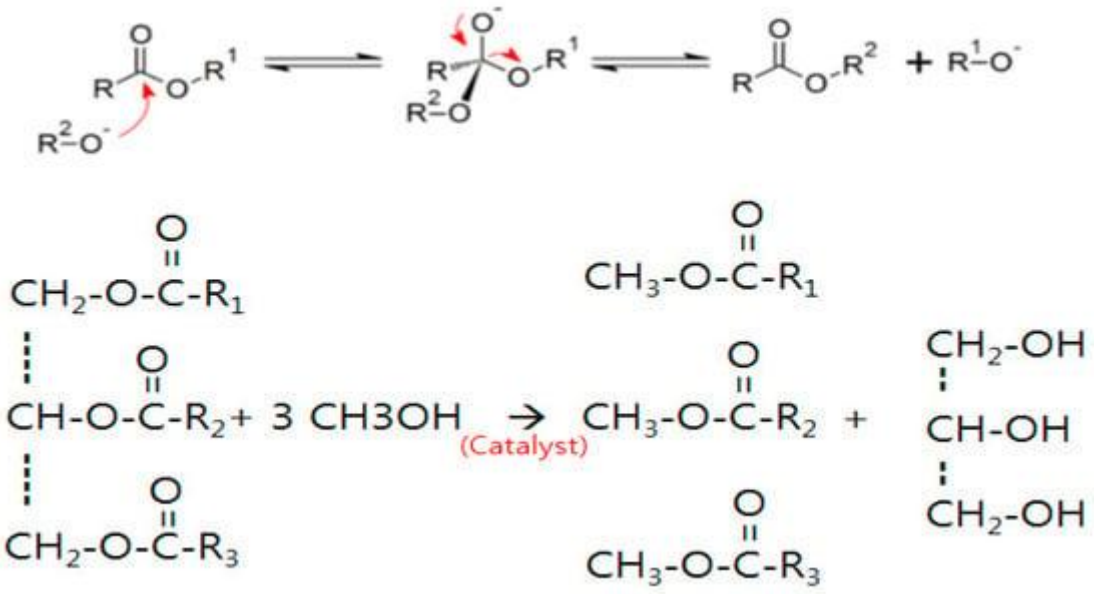


*Figure 2- 7: Schematic diagram of transesterification mechanism, where R1, R2, and R3 are the long hydrocarbon chains (also called the fatty acid chains) (Ge et al., 2017).*

### 2.10.1. Transesterification of Waste Cooking Oils

Waste cooking oils, a substantial byproduct from various sources including vegetable oil refineries, restaurants, and animal slaughterhouses, are economically viable for biodiesel production (Al-Saadi et al., 2020). Waste cooking oil mainly comprises triglycerides, with transesterification converting them into alkyl esters and glycerol in the presence of a catalyst like NaOH or KOH. Low free fatty acid levels facilitate this process, yielding high-purity Fatty Acid Methyl Esters (FAME) (Sujin et al., 2024). However, higher free fatty acid contents often necessitate the use of acid catalysts like H2SO4 for improved yield and purity (Ambawatte et al., 2020). The transesterification process involves three steps, starting with the formation of triglycerides from triglycerides and methanol under agitation, followed by the conversion to monoglycerides and glycerin. Stirring enhances mass transfer, crucial for achieving better miscibility and optimal reaction kinetics, with stoichiometric ratios of one mole of oil reacting

with three moles of alcohol. Adjustments in alcohol molar ratio may be necessary based on oil type, catalyst, and process parameters (Salaheldeen et al., 2021). Reaction temperature typically ranges from 50–75 °C under atmospheric pressure, ideal for biodiesel production.

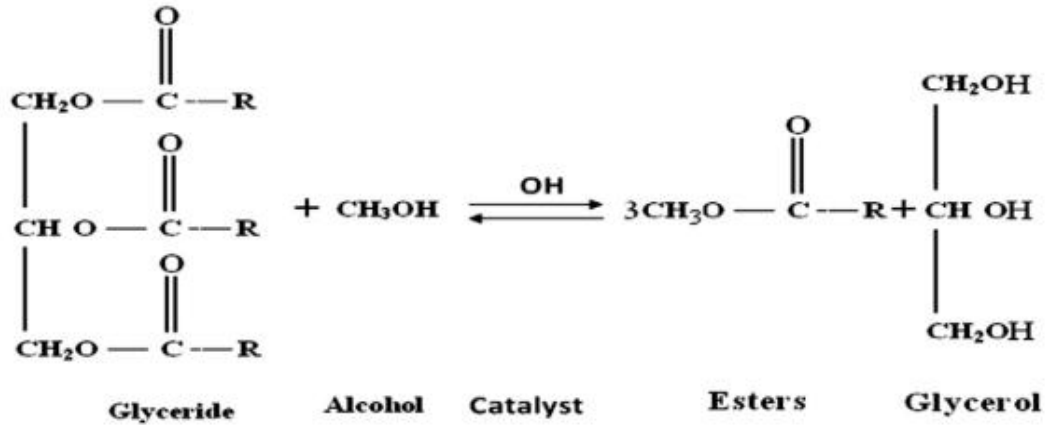


*Figure 2- 8: Transesterification process.*

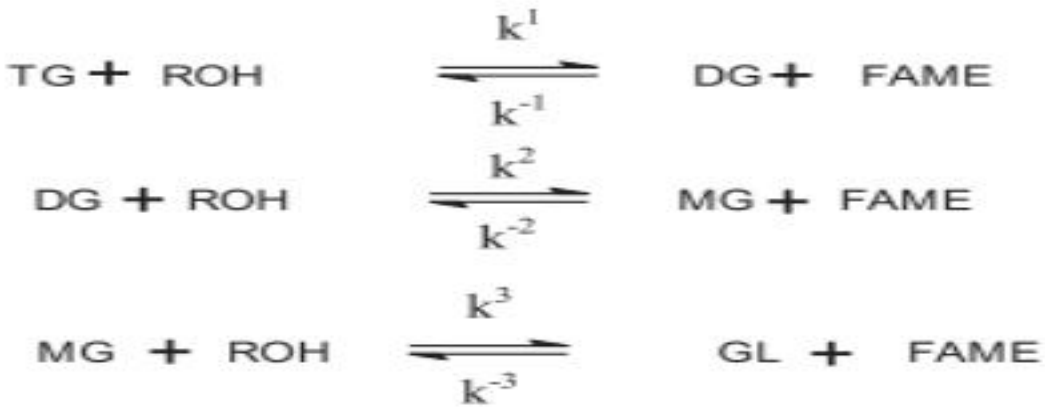


*Figure 2- 9: Overall transesterification reaction*

## 2.11. BLEND OF WASTE COOKING OIL AND PETROL–DIESEL AS A PROMISING RENEWABLE ENERGY FUEL

The global energy crisis, coupled with escalating greenhouse gas emissions and the depletion of fossil fuel reserves, has necessitated the exploration of sustainable alternatives to petroleum-

based fuels (Akhihiero, 2022). Biodiesel, especially that produced from non-edible vegetable oils and waste cooking oil (WCO), has gained attention as a viable renewable substitute for diesel fuel due to its biodegradability, reduced emissions, and renewability (Oyedepo et al., 2019).

Initially, edible vegetable oils were considered for biodiesel production; however, due to food security concerns and high costs, attention shifted to non-edible oils and waste-derived sources, particularly WCO (Naseef & Tulaimat, 2025). Biodiesel is typically synthesized via transesterification, wherein triglycerides from oils or fats react with methanol or ethanol in the presence of catalysts like NaOH or KOH, yielding methyl or ethyl esters (biodiesel) and glycerol (Monika et al., 2023). Diesel engine trials using 20% WCO biodiesel blends have shown modest increases in specific fuel consumption (SFC) and slight reductions in thermal efficiency, attributed to biodiesel's lower calorific value and higher oxygen content (Akhihiero, 2022; Monika et al., 2023).

Blends of waste edible oils (WEO) and conventional diesel offer promising environmental and economic benefits. Utilizing WEO for energy production helps mitigate improper waste disposal, reduces environmental contamination, and contributes to circular economy goals (Naseef & Tulaimat, 2025). Renewable fuels like biodiesel significantly reduce $CO_2$, CO, hydrocarbons (HC), and particulate matter emissions when compared to petroleum diesel (Akhihiero, 2022). However, $NO_x$ emissions are often slightly elevated due to higher combustion temperatures and oxygen availability (Kumar et al., 2025).

Although complete replacement of fossil fuels remains challenging due to supply limitations and engine compatibility, partial substitution using biodiesel blends is both practical and beneficial. Numerous studies confirm that biodiesel blends (B5–B30) can be utilized in CI engines with minimal or no engine modifications (Sujin et al., 2024).

Biodiesel derived from various feedstocks such as sunflower and olive oil, fish oil, palm oil, castor oil, cottonseed oil, almond oil, pongamia oil, rapeseed oil, jatropha oil, mahua oil, waste rapeseed and corn oil, rice bran, safflower oil and milk scum oil, and mustard oil, has been widely studied (Monika et al., 2023). These biodiesel types generally yield lower emissions compared to petroleum diesel, especially in terms of CO, HC, and PM, though increases in $NO_x$ are common across feedstocks. Notably, engine performance and emissions vary depending on the biodiesel feedstock, blending ratio, and engine type, making comprehensive testing essential for optimization (Rathore et al., 2019).

## 2.12. OVERVIEW OF COMPRESSION IGNITION (CI) ENGINES

Compression Ignition (CI) engines, commonly referred to as diesel engines, are internal combustion engines where fuel ignition occurs due to the high temperature generated by compressing air, rather than by spark plugs as in Spark Ignition (SI) engines. First conceptualized by Rudolf Diesel in the late 19th century, CI engines have become the dominant power source for heavy-duty vehicles, agricultural machinery, ships, and generators due to their superior thermal efficiency, durability, and torque output (Rathore et al., 2019).

A typical CI engine operates on the Diesel cycle, which consists of four main strokes: intake, compression, power (expansion), and exhaust. During the compression stroke, air is compressed to a high pressure and temperature (up to ~900 °C), after which fuel is injected directly into the combustion chamber. The fuel spontaneously ignites due to the elevated temperature of the compressed air, causing a controlled explosion that drives the piston downward (P. Breeze, 2018a).

CI engines are generally more fuel-efficient than SI engines, largely due to their higher compression ratios (14:1 to 22:1) and lean-burn operation. However, they tend to emit higher

NOx and particulate matter, necessitating strategies such as Exhaust Gas Recirculation (EGR), Diesel Particulate Filters (DPF), and Selective Catalytic Reduction (SCR) to comply with environmental regulations (P. Breeze, 2018b).

### 2.10.1. CI Engines and WCO-Diesel-Petrol Blends

CI engines have demonstrated notable versatility in fuel compatibility, particularly in accepting biodiesel and diesel blends without significant modifications. Recent advancements have focused on utilizing waste-derived biofuels, such as Waste Cooking Oil (WCO) biodiesel, blended with diesel or other fuels like petrol (gasoline) to enhance combustion properties and reduce emissions (Venkatesan et al., 2024). While petrol improves volatility and cold-start behavior, WCO biodiesel contributes oxygen-rich molecules that promote cleaner combustion. Together, they offer potential for balanced performance, emissions control, and sustainability. This will enhance atomization, reduce ignition delay, and moderate exhaust emissions like carbon monoxide and hydrocarbons, though NOx levels may still require attention (Venkatesan et al., 2024).

Studies have shown that biodiesel blends such as B20 or B30 (20–30% biodiesel with diesel) maintain engine durability and efficiency while reducing dependence on fossil diesel. Moreover, blends with petrol additions are gaining traction as transitional fuels, especially in regions lacking stringent fuel infrastructure but abundant in waste oil (Hasan & Rahman, 2017).

## 2.13. Technical and Economic Feasibility Overview

The technical and economic feasibility of utilizing waste cooking oil (WCO)–based biodiesel blended with petrol and diesel depends on several factors, including fuel properties, engine compatibility, production cost, and environmental performance (Hasan & Rahman, 2017). From

a technical standpoint, WCO biodiesel exhibits favourable fuel characteristics such as higher cetane number, better lubricity, and the presence of oxygenated compounds that promote more complete combustion. When blended with diesel and petrol, these properties enhance atomization and ignition, improving engine efficiency while reducing harmful emissions such as carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM). However, slight increases in nitrogen oxides ($NO_x$) emissions are often observed due to higher in-cylinder combustion temperatures (Hussain et al., 2016).

WCO–diesel–petrol blends have demonstrated technical viability in compression ignition (CI) engines without major modifications. Studies indicate that blends containing up to 20–30% biodiesel (B20–B30) maintain stable engine operation, torque output, and thermal efficiency comparable to pure diesel. The inclusion of small petrol fractions further improves fuel volatility, cold-start behaviour, and overall combustion stability, particularly in low-temperature conditions. Thus, these blends present an efficient transitional fuel option for regions with limited infrastructure for full biodiesel deployment while still providing measurable emission and sustainability benefits (Hasan & Rahman, 2017).

From an economic perspective, WCO offers a cost-effective and sustainable feedstock alternative due to its wide availability and minimal purchase cost. The economic feasibility of biodiesel production from WCO is primarily determined by feedstock collection, pretreatment, transesterification, purification, and blending operations (Monika et al., 2023). Average production costs reported in recent literature range between US$0.90 and US$1.10 per litre, depending on process efficiency, catalyst type, and local feedstock logistics (Kumar et al., 2025). For instance, Zhang et al. (2021) found that WCO-based biodiesel production costs were approximately 65% higher than conventional diesel at small-scale operations; however, large-

scale plants reduced production costs by up to to 20% through by-product valorization, particularly from glycerol recovery. Similarly, Bunyakiat et al. (2024) reported that a 150 L batch production system achieved a break-even point of approximately 42,000 L per year and a payback period of less than three years when biodiesel was marketed competitively.

In developing economies such as Nigeria, where diesel and petrol prices fluctuate due to foreign exchange dependence and importation costs, the local production of WCO-derived biodiesel blends offers a significant economic advantage. By converting domestic waste into energy, this approach supports circular economy objectives, reduces environmental pollution, and enhances energy security (Oyedepo et al., 2019). Furthermore, potential fiscal incentives such as carbon credits, renewable energy subsidies, and tax reliefs could further improve the profitability of biodiesel production and distribution networks.

Nevertheless, certain constraints limit full economic competitiveness. The logistics of WCO collection, quality variability, and pre-treatment requirements can increase operational costs, especially when waste sources are decentralized or contaminated with water and food residues (Rahman et al., 2024). Additionally, biodiesel's lower calorific value can result in slightly higher specific fuel consumption (SFC), offsetting some cost savings achieved from cheaper feedstocks (Monika et al., 2023). These challenges can be mitigated through optimized supply chain management, improved catalyst efficiency, and process intensification techniques to enhance conversion yield and lower production energy input (Rahman et al., 2024).

# CHAPTER THREE

# MATERIALS AND METHODS

**Introduction:**

This chapter explains the experimental procedures and list of equipments and reagents used for his research.

## 3.1. MATERIALS

### 3.1.1. Reagents and Raw Materials Used

Waste cooking oil was acquired from restaurants and canteens around the school environment, the University of Benin, Benin City, Nigeria, and neighboring roadside bean cake vendors around the school locality.

The reagents used are listed below;

(i). Distilled water

(ii). Methanol

(iii). NaOH

(iv). Benzene

(v). Phenolphthalein indicator

(vi). Ethanol

(vii). Detergent

(viii). Sulphuric acid ($H_2SO_4$)

### 3.1.2. List of Equipment / Apparatus

i. Digital scale

ii. Conical flask

iii. Dropper

iv. Syringe

v. Density bottle

vi. Laboratory pestle

vii. Laboratory mortal

viii. Hang gloves

ix. Stirrer

x. Magnetic stirrer

xi. Funnel

xii. Measuring Cylinder

xiii. Round bottom flask

xiv. Muffle furnace

xv. Oven

xvi. Crucibles

xvii. Beakers

xviii. Heating mantle

xix. Desiccator

xx. Retort stand

xxi. Viscometer

xxii. Pipette

xxiii. Centrifuge

xxiv. Burette

## 3.2. METHODS

### 3.2.1. The Physicochemical Properties of the Oil Used

#### 3.2.1.1. Density

The exact addition of waste cooking oil to a density container with a defined volume marked the beginning of the testing procedure. The first thing that needed to be done was weigh the empty bottle using a high-precision weighing balance. After that, there was one more weighing that included the bottle and the oil. The measured values were recorded with great care. The resulting weight shift, which was calculated by deducting the empty bottle's original weight from the oil and bottle's combined weight, took on significant importance. This computed weight change was crucial in determining the oil's weight-to-mass ratio. Utilizing this established ratio, the next step involved the computation of the oil's density by dividing its mass by the known volume of the density bottle.

$$Density = \frac{Mass}{Volume} \qquad 0\text{-}1$$

#### 3.2.1.2. Moisture content

The procedure involved introducing waste cooking oil (WCO) into a beaker with a predetermined mass. Using a precision balance, the total weight of the beaker and oil was measured before being allowed to evaporate for an hour at 120°C in the oven. Following the completion of the evaporation process, the weight of the beaker and the desiccated oil was re-measured and recorded. The percentage of moisture content was computed employing the subsequent formula:

$$Moisture\ content\ = \frac{w_1 - w_2}{w_1 - w_0} \qquad 0\text{-}2$$

Where;

$w_0$ = weight of empty beaker

$w_1$ = weight of beaker and oil before evaporation

$w_2$ = weight of beaker and oil after evaporation

### 3.2.1.3. Acid Value

An initial analysis was carried out to determine the amount of free fatty acids present in the used cooking oil (WCO) before the biodiesel synthesis process was started. It was necessary to weigh out one gram of residual cooking oil and pour it into a conical flask. After that, 10ml each of benzene and ethanol were added to the flask in equal amounts. Carefully stirring the ensuing amalgamation helped to facilitate the dissolution of the oil. The final step involved titrating the resulting solution against a 0.05N KOH solution. As part of the titration method, three drops of phenolphthalein were administered as an indicator. To start the titration process, the KOH solution was gradually added to the mixture of oil, alcohol, and phenolphthalein.

This addition was accompanied by thorough shaking until the solution maintained a continuous pink hue for a duration of 20 seconds.

$$Acid\ Value\ = \frac{N \times 56.1 \times (V_s - V_b)}{weight\ of\ oil\ of\ sample} \qquad 0\text{-}3$$

$$FFA = \frac{Acid\ Value}{2} \qquad 0\text{-}4$$

Where;

$V_S$ = Volume of 0.05N KOH used with oil

$V_b$= Volume of 0.05N KOH used without oil (Blank)

N = Concentration of KOH

### 3.2.1.4. Saponification Value

The average molecular weight of the fatty acids present in a sample as triglycerides is determined by the saponification value. It shows the milligrams of potassium hydroxide (KOH) or sodium hydroxide (NaOH) needed to fully saponify one gram of fat in accordance with particular recommendations (Bello et al., 2015). A conical flask was filled with an exact 2-gram quantity of the oil sample to start the procedure. Next, the liquid in the pipette was able to empty completely after carefully pipetting 5 ml of an alcohol potassium hydroxide solution into the flask. The mixture underwent heating and boiling on a sand bath under an air condenser setup for approximately 50 minutes. The solution exhibited a change in clarity and homogeneity during boiling, indicating the conclusion of the saponification process. A blank sample was analysed using a similar process. After boiling, the mixture was taken out of the sand bath and given a quick rinse with distilled water to make it easier for the parts that were attached to slide down the sides of the flask. After adding 1 ml of an indicator, the contents of the flask were allowed to cool. 0.5M HCl was added to the solution and titrated until the pink hue vanished. A particular relationship was used to determine the oil's saponification value.

$$Saponification\ Value\ = \frac{56.1 \times N \times (V_b - V_s)}{weight\ of\ oil\ of\ sample} \qquad 0\text{-}5$$

Where;

$V_S$ = Sample titre value

$V_b$= Blank titre value

N = Concentration of HCl

### 3.2.1.5. Kinematic Viscosity

The Brookfield NDJ-5S Rotary viscometer was used in the determination of viscosity. The appropriate spindle number was identified and selected for the test sample and gently mounted on the machine. A 250ml beaker was cleaned, and the sample was poured up to the 200ml mark. The beaker was then placed on a water bath with the temperature preset at a constant 30 °C and allowed to equilibrate for 10 minutes. The spindle and the temperature sensor of the machine were then lowered into the sample, and the power button was turned on. The appropriate spindle number and speed were selected on the display screen, followed by the run button. The machine was then allowed to read the viscosity until a stable value was obtained and recorded.


*Figure 3- 1: Digital rotary viscometer*

### 3.2.1.7. Specific gravity

A simple procedure was used to ascertain the waste cooking oil (WCO) sample's specific gravity. Initially, a dry, clean, 25 ml density container was determined and noted as m1. The combined mass of the water and the bottle was measured and recorded as m2 after the addition of distilled water. The remaining vegetable oil was poured into the bottle, and the mass was measured in milliliters (mL). Next, the following formula was used to determine the oil sample's specific gravity:

$$Specific\ gravity = \frac{m_3 - m_1}{m_2 - m_1} \qquad 3.6$$

### 3.2.2. Esterification Reaction

A measured 1000 g of waste cooking oil (WCO) was placed in a round-bottom glass reactor and subjected to esterification using methanol at 25 wt.% in the presence of 1.0 wt.% sulfuric acid ($H_2SO_4$) as a catalyst. This process aimed to reduce the free fatty acid (FFA) content to approximately 1%, following the method described by Oshomogho & Okologume (2024). The mixture was heated and continuously stirred on a magnetic stirrer maintained at a constant temperature of 60 °C for 1.5 hours. The process was repeated until the FFA level reached about 1%. After esterification, the treated WCO appeared significantly clearer and lighter in color compared to the raw sample, indicating that most of the free fatty acids had been successfully removed.

### 3.2.3. Transesterification Reaction

In this study, biodiesel was efficiently produced from waste cooking oil (WCO) through a transesterification process using methanol in a 2000 mL round-bottom flask reactor, following the procedure outlined by Putra et al. (2020). The reactor was preheated to the desired temperature, after which 1000 g of esterified WCO was introduced. A prepared mixture of methanol and catalyst was then added, and the reaction was carried out under continuous

agitation at 300 rpm. Transesterification is a chemical process in which triglycerides are converted into biodiesel and glycerol using a strong base catalyst such as potassium hydroxide (KOH) or sodium hydroxide (NaOH) (Kiprono et al., 2022). In this procedure, the catalyst was first dissolved in methanol before being added to the esterified WCO. The reaction was maintained at a temperature range of 60 to 70 °C for approximately one to two hours. Upon completion, the reaction mixture was transferred into a separating funnel where two distinct layers formed due to density differences, with the lower layer consisting of dense dark glycerol and the upper layer being a clear yellow biodiesel phase (Mahmood et al., 2022). The biodiesel layer was carefully separated and washed with water several times to remove residual catalysts and impurities. The purified biodiesel obtained from this process is suitable for direct use in diesel engines. As a renewable and environmentally friendly fuel, biodiesel contributes to reduced greenhouse gas emissions and improved air quality. Finally, the biodiesel yield was determined by weighing the product according to the prescribed procedure.

$$Yield\ of\ Biodiesel\ = \frac{grams\ of\ biodiesel\ produced}{gramsof\ oil\ used} \times 100\% \qquad 0.7$$

### 3.2.4. Crude Biodiesel Purification

The crude biodiesel was purified using warm water after the initial separation in a separating funnel to ensure maximum separation efficiency. To prevent the formation of emulsions and allow the smooth passage of water droplets through the ester phase, the crude biodiesel was gently mixed with warm water and lightly agitated. This washing procedure was repeated several times until the rinse water appeared clear, signifying that all residual impurities and contaminants had been successfully removed from the biodiesel.

### 3.2.5. Blending Methodology

After producing biodiesel through the transesterification of waste cooking oil, a biodiesel fuel blend was prepared by mixing a series of biodiesels ranging from B10, B15, B20, and B25 by volume of the biodiesel with 90%, 85%, 80%, and 75% conventional diesel, respectively. The blending was carried out at room temperature in a clean, airtight container using manual stirring to ensure homogeneity. The blended fuel was then allowed to settle for 24 hours to eliminate any entrained air or impurities before being used in the engine performance and emission testing on a compression ignition engine (Abed et al., 2018; Sleem et al., 2024; Solangi et al., 2022).

### 3.2.5. Gasoline Engine Test on Biodiesel Fuel Blend

The performance of biodiesel fuel blends was evaluated using a single-cylinder, 2.0 hp gasoline engine coupled to a single-phase 220V, 1.5 kW alternator at Luco Chemical Laboratory Ltd, Benin City. This type of engine is typically employed for medium-scale power generation. The setup included an exhaust gas analyzer, a digital tachometer, and a digital rotameter connected directly to the engine. Before testing the biodiesel blends, the engine was first operated on gasoline (PMS) for several minutes to allow it to reach steady operating conditions. Afterward, it was run with each biodiesel and conventional diesel blend before being shut down, following the same procedure for every test fuel. For the performance test, the engine was operated at full load with the throttle completely open. Exhaust gases, including NOx/NO, HC, $H_2S$, and CO, were measured using a BOSCH BEA-350 exhaust gas analyzer. Emission data were recorded at a constant engine speed of 2000 rpm. Fuel flow was monitored using a digital rotameter-type flow meter, while the temperatures of the engine oil, cooling water, exhaust gas, and inlet air were recorded using K-type thermocouples (Oshomogho & Okologume, 2024).

### 3.2.6. Engine Performance and Emission Study

The performance and emission characteristics of the engine operating on various biodiesel blends and conventional petroleum diesel were analyzed in terms of Brake Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE). Biodiesel blends of B10, B15, B20, and B25 were prepared by mixing synthesized biodiesel with conventional diesel and tested at a constant load of 3000 W to assess the behavior of the fuel in a compression ignition (CI) engine.

The exhaust gases, which are carbon monoxide (CO), nitrogen oxides (NOx), carbon dioxide ($CO_2$), and hydrocarbons (HC), were measured using an exhaust gas analyzer. Fuel consumption rates were determined under varying loads for each blend. The parameters, including brake torque, brake power (BP), BSFC, and BTE, were computed following the procedures described by (a V S L et al., 2021), as presented in Equations (3.6) to (3.7).

**Brake Power (BP)**

$$Brake\ Power\ (BP) = \frac{2\pi N(WR_e(9.81))}{60000} \qquad 3.8$$

Where

N is engine speed (3000 rpm)

W is the load applied to the engine (3,000W)

Re is the effective radius of the brake drum (2.0cm)

**Brake Mean Effective Pressure (BMEP)**

$$Break\ Mean\ Effective\ Pressure\ (BMEP) = \frac{BP60}{SVN} \qquad 3.9$$

Where;

SV is stroke volume (5.77cm$^2$)

N is engine speed (3000rpm)

**Total Fuel Consumption**

$$Total\ Fuel\ Consumption\ (TFC) = \frac{S.SG \times 3600}{1000t} \qquad 3.10$$

Where;

SG is the specific gravity of fuel

T is time for 5cc fuel consumption in seconds

**Brake Specific Fuel Consumption and Brake Thermal Efficiency**

$$Brake\ Specific\ Fuel\ Consumption\ (BSFC) = \frac{TFC}{BP}(kg/kWh) \qquad 3.11$$

$$Brake\ Thermal\ Efficiency\ (BTE) = [\frac{BP \times 3600}{TFCC_v}] \qquad 3.12$$

Where;

$C_v$ is the calorific value of fuel. (Amount of energy that is discharged when a unit quantity of fuel burns). The test fuels would be petroleum diesel and diesel blends with castor and jatropha biodiesel. The fuels were blended by using an overhead mixer/homogenizer device at a speed of 3000 rpm for 10 min.

### 3.2.6. Characterization of the blended oil produced

According to the standard specifications provided in ASTM D 6751 and EN 14214, the blended biodiesel-synthesized material was thoroughly characterized (Saad et al., 2023).


*Figure 3- 2: Practical demonstration of the Biodiesel yield*


*Figure 3- 3: Practical demonstration of the Biodiesel yield*

*Figure 3- 4: Biodiesel Plant set up at LUCO Chemical Laboratory Ltd*

# CHAPTER FOUR

# RESULT AND DISCUSSION

## 4.1 Results of Physical and Chemical Analysis of Waste Cooking Oil

Table 4.1 summarizes the findings of the analysis conducted on the composition of waste cooking oil. The percentage of FFA was found to be 2.5245%, derived from an acid value of 5.049 mg KOH/g. Research indicates that high FFA levels can reduce biodiesel yield and affect process efficiency. Therefore, it is recommended that the FFA in WCO should not exceed 2 wt.% for optimal conversion (Kawentar & Budiman, 2013; Sarno & Iuliano, 2019). Although no catalyst was used in this study, the FFA value obtained reflects the oil's acidity and suitability for pretreatment before biodiesel production. The moisture content of the WCO was 0.20 wt%,

which is below the critical limit (≥0.5 wt%) stated in the literature to hinder biodiesel yield. Low moisture content minimizes hydrolysis and soap formation, improving the oil's quality. The density of the oil was 0.931 g/ml, which falls within the range typical of vegetable oils (0.90–0.94 g/ml) used for biodiesel synthesis (Oshomogho & Okologume, 2024).

Visual examination showed the waste cooking oil to be light brown and clear, indicating filtration and settling before analysis (Rahmayanti et al., 2021). These results show that the oil possesses favorable properties such as low moisture and suitable density, and the high FFA level shows that pretreatment is required before transesterification for optimal biodiesel yield.

*Table 4.1: : Physical and Chemical Analysis of Waste Cooking Oil*

| **Property (Unit)** | **Value** | **Remarks / Reference** |
|---|---|---|
| Density (g/ml) | 0.931 | Within 0.90–0.94 range (Linganiso et al., 2022). |
| Moisture content (wt%) | 0.20 | Below the 0.5 wt.% limit (Linganiso et al., 2022). |
| Acid value (mg KOH/g) | 5.049 | Indicates moderate acidity (Linganiso et al., 2022) |
| Free Fatty Acid (FFA, %) | 2.5245 | Slightly above ideal 2 wt.% (Kawentar & Budiman, 2013; Sarno & Iuliano, 2019). |
| Colour/Appearance | Light brown, clear | Filtered and settled oil (Rahmayanti et al., 2021). |

### 4.1.1 Esterified WCO Results

The esterification pre-treatment utilized a total oil mass of 1,584.408 g. Based on this, methanol and sulphuric acid were added at 23 wt.% and 1 wt.%, corresponding to 364.41 g and 15.84 g,

respectively. After esterification and settling, two layers were formed: an upper phase of methanol and dissolved free fatty acids, and a lower phase containing the esterified oil (Oshomogho & Okologume, 2024). The esterified parameters and the quantitative result are presented in Table 4.2.

*Table 4.2:Esterification Parameters and Quantitative Results*

| **Parameter** | **Value (g)** | **Percentage of Oil Mass (%)** |
|---|---|---|
| Total oil mass | 1,584.408 | 100 |
| Methanol added | 364.41 | 23 |
| Sulphuric acid added | 15.84 | 1 |

The results indicate that the proportions of methanol and acid catalyst were sufficient for efficient pretreatment, producing a distinct separation between esterified oil and methanol-rich layers.

### 4.2 Physical and Chemical Properties of Waste Cooking Oil (WCO) Biodiesel

The biodiesel obtained from the transesterification of waste cooking oil was evaluated for its quality and compliance with ASTM standards for pure biodiesel (B100), which serve as guidelines for fuel performance and usability either alone or in blend with diesel fuel (Masjuki et al., 2013). The transesterified oil was thoroughly washed with water and dried before analysis. The main properties examined include viscosity (ASTM D93), acid value (ASTM D664), oxidative stability (EN 14112), and flash point. All evaluated parameters fell within the ASTM-specified range, as presented in Table 4.3. The transesterification reaction was carried out using 1651.934 g of esterified oil. Before the reaction, the acid value of the esterified oil was determined as 0.84 mg KOH/g, corresponding to a free fatty acid (FFA) value of 0.42%,

indicating effective pretreatment and suitability for base-catalyzed transesterification. The reaction mixture consisted of 23% methanol (379.94 g) and 1% sodium hydroxide (16.52 g), stirred magnetically for 1 hour and then left to settle for 24 hours. The alkyl ester layer (biodiesel) formed the top phase, while excess methanol and impurities settled at the bottom (Oshomogho & Okologume, 2024).

*Table 4.3: Physical and Chemical Properties of Waste Cooking Oil (WCO) Biodiesel*

| **Property (Unit)** | **Measured Value** | **ASTM Biodiesel Standard** | **Remarks** |
|---|---|---|---|
| Biodiesel Yield (%) | 91.842 | NA | High yield after pretreatment |
| Density @ 30°C (g/ml) | 0.860 | 0.86–0.90 | Within acceptable range |
| Density | 0.854 | 0.88 | Acceptable |
| Dynamic Viscosity (mPa·s) | 4.49 | 1.9–6.0 | Within limit |
| Kinematic Viscosity @ 30°C ($mm^2/s$) | 5.68 | NA | Acceptable |
| Flash Point (°C) | 128 | 100–170 | Meets ASTM D93 |
| Moisture Content (%) | 0.11 | <0.5 | Good fuel stability |
| Acid Value (mg KOH/g) | 0.43 | <0.5 | Within limit |
| Free Fatty Acid (FFA, %) | 0.21 | NA | Low acidity |
| Oxidative Stability | 4 hr 25 min | >3 hrs | Satisfactory |
| Colour/Appearance | Light yellow, clear | NA | Indicates proper washing and drying |

The resulting biodiesel displayed a density of 0.860 g/ml, acid value of 0.43 mg KOH/g, FFA of 0.21%, and a moisture content of 0.11%. Its flash point (128°C) and kinematic viscosity (5.68 $mm^2/s$) were both within ASTM D6751 limits, confirming safety and good flow behavior during combustion. The measured oxidative stability was 4 hours 25 minutes, slightly above the 3-hour minimum requirement, which shows good resistance to degradation. These results confirm that

the WCO biodiesel produced meets major ASTM specifications, indicating its suitability for use as an alternative renewable fuel (Linganiso et al., 2022).

### 4.3. Effects of Blend on Fuel Properties

The experimental evaluation of blended fuels demonstrated that incorporating biodiesel produced from waste cooking oil (WCO) influenced the physical and combustion characteristics of petroleum diesel. As shown in Table 4.4, blending biodiesel with petroleum diesel caused variations in calorific value, density, viscosity, and fuel consumption. According to international standards, the "B" notation represents the percentage of biodiesel in a blend, where pure diesel (B0) contains no biodiesel, and B10, B15, B20, and B25 contain 10%, 15%, 20%, and 25% biodiesel, respectively (Attia & Hassaneen, 2015).

*Table 4.4: Properties of Petroleum Diesel and Waste Cooking Oil Biodiesel Blends*

| **Property** | **B10** | **B15** | **B20** | **B25** | Petrol-Diesel (ASTMD975) |
|---|---|---|---|---|---|
| Time (minutes) | 3.56 | 4.73 | **3.93** | 4.14 | NA |
| Calorific Value (MJ/kg) | 43.013 | 42.722 | **42.050** | 41.892 | 45.0-45.5 |
| Density (g/cm³) | 0.8533 | 0.8596 | **0.8624** | 0.8681 | 0.82-0.85 |
| Mass of Fuel (g) | 85.33 | 85.96 | **86.24** | 86.81 | NA |
| Viscosity (mPa·s) | 2.34 | 2.62 | **3.61** | 3.43 | 1.9-6.0 |
| Fuel Consumption (g/hr) | 1438.147 | 1090.402 | **1316.641** | 1258.116 | NA |
| Flash Point (°C) | 62 | 67 | **71** | 78 | Min. 52-60 |
| Acid Value (mgKOH/g) | 0.22 | 0.243 | **0.23** | 0.28 | Max 0.3-0.5 |

The results show that as the proportion of biodiesel increased from B10 to B25, the calorific value gradually decreased from 43.013 MJ/kg to 41.892 MJ/kg. This reduction is consistent with findings that biodiesel possesses a slightly lower heating value than conventional diesel due to its oxygenated nature and fatty acid composition (El-Aziz Mohamed et al., 2021). Despite this reduction, the calorific values remain within acceptable operational limits for diesel engines.

The density of the blends increased from 0.8533 for B10 to 0.8681 for B25, reflecting the higher density of biodiesel compared to petroleum diesel. This increase enhances lubricating properties but can slightly influence fuel atomization. The viscosity of increased with increasing biodiesel blend concentration ranging from 2.3 mpa.s for B10 to 3.43 mpa.s for B25 which falls within the ASTM D445 specification range (1.9–6.0 mPa·s), indicating proper flow behavior suitable for injection and combustion. The flash point of the fuel rises significantly with higher biodiesel blends. This means the fuel becomes much safer to handle and store because it is less likely to ignite accidentally. Fuel consumption decreased with increasing biodiesel concentration, ranging from 1438.15 g/hr for B10 to 1258.12 g/hr for B25. This reduction shows improved combustion efficiency at higher biodiesel proportions, attributed to the oxygen-rich composition of biodiesel, which promotes more complete combustion.

Additionally, the B20 blend (20% biodiesel and 80% diesel) demonstrated the most balanced performance among all the tested samples. It combined efficient combustion, moderate fuel consumption (1316.64 g/hr), and a calorific value of 42.05 MJ/kg, while maintaining an acceptable Density (0.8624) and viscosity (3.61 mPa·s). This indicates that the 20:80 ratio provided an optimal trade-off between energy content, fuel economy, and emission potential (Akhihiero, 2022). It retained sufficient heating value for effective power generation while offering the environmental and lubricating advantages of biodiesel (Harari et al., 2019). These

results show that blending WCO biodiesel with diesel fuel, particularly at the 20:80 ratio (B20), enhances combustion stability and fuel economy while maintaining physical properties within acceptable limits. This confirms the suitability of B20 WCO biodiesel blends as viable renewable alternatives to fossil diesel in compression ignition engines (Harari et al., 2019; Jeevahan et al., 2016).

### 4.4. Effects of Blends on Engine Exhaust Gas

Nitrogen dioxide ($NO_2$) is a highly toxic emission produced from diesel engine combustion. Unlike nitrogen monoxide (NO), $NO_2$ poses serious health hazards because it reacts with water in the eyes, lungs, mucous membranes, and skin to form nitric acid ($HNO_3$), which contributes to respiratory irritation and environmental acidification (Liaquat et al., 2014). The results presented in Table 4.5 indicate that increasing the proportion of biodiesel in diesel fuel substantially influences the composition of exhaust gases, particularly by reducing nitrogen oxide (NOx) and sulfur dioxide ($SO_2$) emissions.

*Table 4.5: Effects of Blends on Exhaust Emissions*

| **Property** | **B10** | **B15** | **B20** | **B25** |
|---|---|---|---|---|
| CO (ppm) | 0.00 | 0.00 | 0.00 | 0.00 |
| $CO_2$ (ppm) | 826 | 747 | 762 | 678 |
| Sound (dBA) | 100.7 | 106.7 | 105.4 | 108.6 |
| TVOC ($mg/m^2$) | 0.136 | 0.238 | 0.342 | 0.388 |
| $SO_2$ (ppm) | 8.6 | 6.3 | 6.1 | 4.2 |
| NOx (ppm) | 112 | 68 | 66 | 67 |
| $H_2S$ (ppm) | 0.00 | 0.00 | 0.00 | 0.00 |

As the biodiesel content increased from B10 to B25, a steady reduction in NOx and $SO_2$ emissions was observed. The NOx concentration decreased from 112 ppm at B10 to 67 ppm at B25, while $SO_2$ dropped from 8.6 ppm to 4.2 ppm. This behavior can be attributed to the oxygen-rich molecular structure of biodiesel, which promotes more complete combustion and reduces the availability of nitrogen and sulfur species that form these pollutants. The findings confirm that biodiesel enhances combustion quality and lowers the release of harmful exhaust gases compared to pure diesel. Carbon dioxide ($CO_2$) emissions followed a decreasing trend with higher biodiesel content, declining from 826 ppm at B10 to 678 ppm at B25. This reduction signifies a lower carbon footprint and supports the use of biodiesel blends as a sustainable fuel option. Carbon monoxide (CO) and hydrogen sulfide ($H_2S$) were not detected in any of the samples, indicating efficient oxidation of carbon and sulfur compounds within the combustion chamber.

A slight increase in total volatile organic compounds (TVOC) was observed with higher biodiesel proportions, ranging from 0.136 mg/m² at B10 to 0.388 mg/m² at B25. This increase may be due to localized incomplete oxidation of heavier hydrocarbon components, which is a typical behavior of biodiesel-rich blends owing to their higher viscosity.

The B20 blend (20% biodiesel and 80% diesel) exhibited the most balanced exhaust gas performance. It achieved a significant reduction in NOx emissions to 66 ppm and $SO_2$ emissions to 6.1 ppm, while maintaining moderate $CO_2$ emissions at 762 ppm and showing no detectable CO or $H_2S$. These results indicate that the B20 ratio provided the optimal balance between emission reduction and combustion efficiency. This further establishes that the 20:80 biodiesel–diesel blend (B20) is the most scientifically and environmentally viable mixture among the tested

samples. It demonstrates efficient combustion, minimized greenhouse gas and sulfur emissions, and stable engine operation, making it a promising renewable alternative for diesel-powered compression ignition engines, as confirmed by Akhihiero (2022).

### 4.5. Effect of Fuel Blending on Fuel Consumption

The variation in fuel consumption (FC) with respect to biodiesel blend ratio is presented in Figure 1. The results revealed a consistent decline in fuel consumption as the proportion of biodiesel increased in the fuel mixture. Specifically, FC decreased from 1438.15 g/hr at B10 to 1258.12 g/hr at B25, representing an overall 12.5% reduction in fuel use with increasing biodiesel concentration. This reduction indicates that biodiesel–diesel blends enhance combustion efficiency due to the inherent oxygenated molecular structure of biodiesel, which supports more complete oxidation of fuel within the combustion chamber. Improved oxidation leads to a decrease in unburned hydrocarbons and reduces the total amount of fuel required to sustain the same output load of 6000 W. These observations are consistent with the findings of Oshomogho & Okologume (2024), who reported that blending biodiesel with diesel significantly lowers specific fuel consumption by improving atomization and air–fuel mixing during injection and combustion. The presence of oxygen in biodiesel facilitates cleaner and more energy-efficient combustion, thereby improving thermal conversion efficiency compared to conventional diesel fuel.

The effect of viscosity was also observed to play a secondary but notable role in fuel consumption. Although pure biodiesel generally exhibits higher viscosity, which can impair fuel spray characteristics, the moderate blending ratios applied in this study (B10–B25) maintained suitable flow properties. This ensured stable combustion and efficient fuel utilization, preventing adverse effects on atomization or ignition delay (Oshomogho & Okologume, 2024). The B20

blend (20% biodiesel and 80% diesel) demonstrated the most balanced performance among all the tested samples. It combined efficient combustion with moderate fuel consumption (1316.64 g/hr) and a calorific value of 42.05 MJ/kg, while maintaining acceptable viscosity and density. This indicates that the 20:80 blend ratio provides an optimal trade-off between energy output, combustion stability, and fuel economy.

In practical application, the findings suggest that waste cooking oil (WCO) biodiesel blends can achieve comparable power output with reduced fuel input, translating to a positive energy balance and improved overall fuel economy. Therefore, the 20% WCO biodiesel blend (B20) represents a technically feasible, cost-effective, and environmentally sustainable fuel alternative suitable for compression ignition engines and stationary power generation systems Akhihiero (2022).

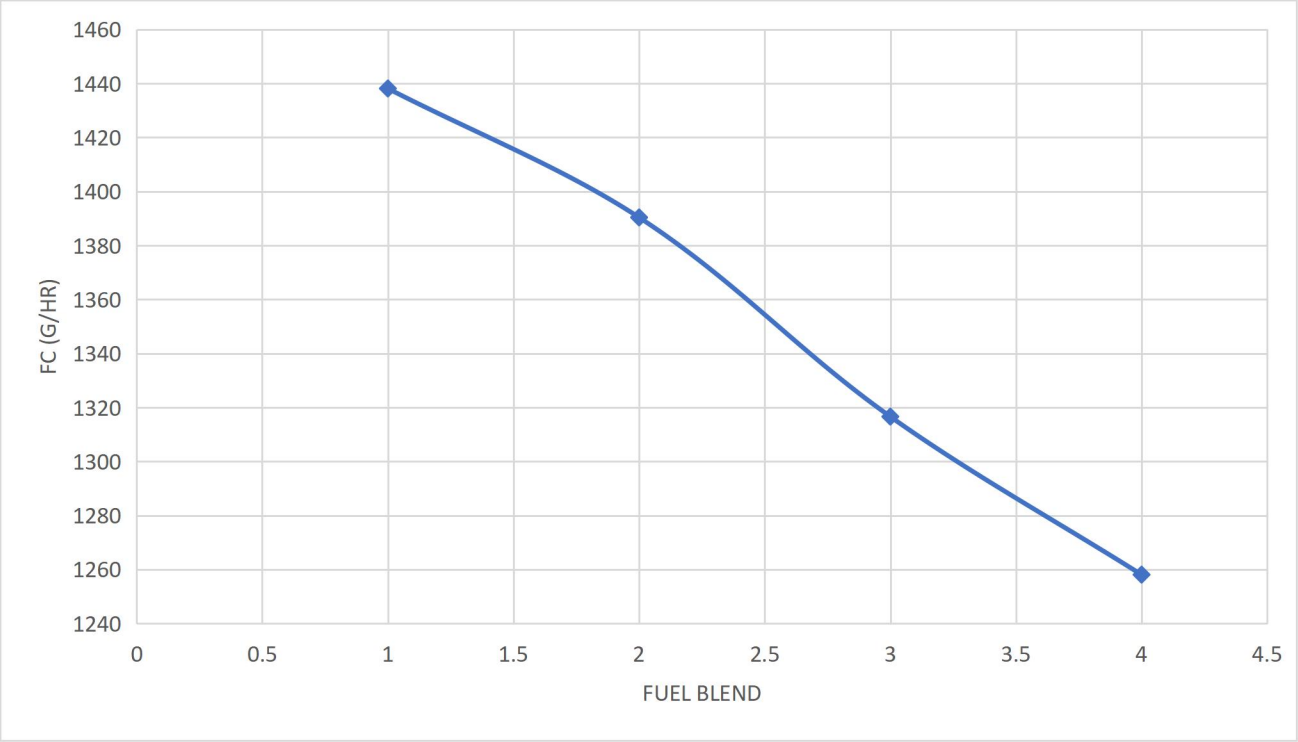


*Figure 4- 1: Effect of Biodiesel Blend Ratio on Fuel Consumption at Constant Load (6000 W)*

### 4.6. Results of Engine Performance Test

The performance of an internal combustion engine fueled with blends of waste cooking oil (WCO) biodiesel and petroleum diesel was evaluated in terms of Brake Mean Effective Pressure (BMEP), Brake Specific Fuel Consumption (BSFC), and Brake Thermal Efficiency (BTE) (Khan et al., 2016). The experiments were conducted under a constant electrical load of 6 kW, and the results are summarized in Table 4.6.

*Table 4.6: Biodiesel Blends on Engine Performance Test*

| **Parameter** | **B10** | **B15** | **B20** | **B25** |
|---|---|---|---|---|
| Time (hr) | 0.0593 | 0.0788 | 0.0655 | 0.0690 |
| Calorific Value (MJ/kg) | 43.013 | 42.722 | 42.050 | 41.892 |
| Density (g/cm³) | 0.8533 | 0.8596 | 0.8624 | 0.8681 |

| | | | | |
|---|---|---|---|---|
| Fuel Consumption (g/hr) | 1438.147 | 1390.402 | 1316.641 | 1258.116 |
| Brake Power (W) | 184.91 | 184.91 | 184.91 | 184.91 |
| Brake Specific Fuel Consumption (kg/kWh) | 7.778 | 6.897 | 6.120 | 5.804 |
| Brake Mean Effective Pressure (BMEP) | 64.094 | 64.094 | 64.094 | 64.094 |
| Brake Thermal Efficiency (BTE %) | 1.076 | 1.129 | 1.202 | 1.263 |

### 4.6.1. Brake Power (BP)

Brake power represents the usable power output of the engine and is directly influenced by torque and rotational speed. The brake power for all tested blends (B10–B25) remained relatively constant at 184.91 W, indicating that increasing biodiesel content did not negatively affect the overall power output of the engine. This stability shows that the calorific value and energy density of WCO biodiesel are sufficient to maintain comparable torque and speed as conventional diesel fuel. According to Oshomogho & Okologume (2024), similar results were observed for biodiesel derived from Luffa cylindrica, where brake power either slightly increased or remained constant with higher blends due to better combustion efficiency and improved cylinder pressure distribution.

### 4.6.2. Rate of Fuel Consumption (FC)

Fuel consumption exhibited a decreasing trend with increasing biodiesel concentration (Figure 2). The measured fuel consumption declined from 1438.15 g/hr for B10 to 1258.12 g/hr for B25, indicating a 12.5% reduction in total fuel usage as the biodiesel proportion increased. This improvement is primarily attributed to the oxygen-enriched molecular structure of biodiesel, which promotes superior atomization and more complete combustion. As a result, less fuel is required to sustain the same power output under identical load conditions.

However, among all the blends, B20 demonstrated the most balanced performance, achieving efficient combustion with moderate fuel consumption of 1316.64 g/hr while maintaining stable engine operation. This finding supports the aim of the study, which was to identify an optimal biodiesel–diesel blend that ensures enhanced combustion efficiency without compromising fuel economy or engine performance. The B20 blend provides sufficient oxygenation to improve fuel–air mixing while retaining adequate calorific value, resulting in a more favorable energy-to-fuel ratio. These results are consistent with similar studies, which reported that higher blends offer the most efficient balance between fuel economy and power output due to optimal viscosity and oxygen content that facilitate complete combustion (Mu et al., 2023; Oshomogho & Okologume, 2024).

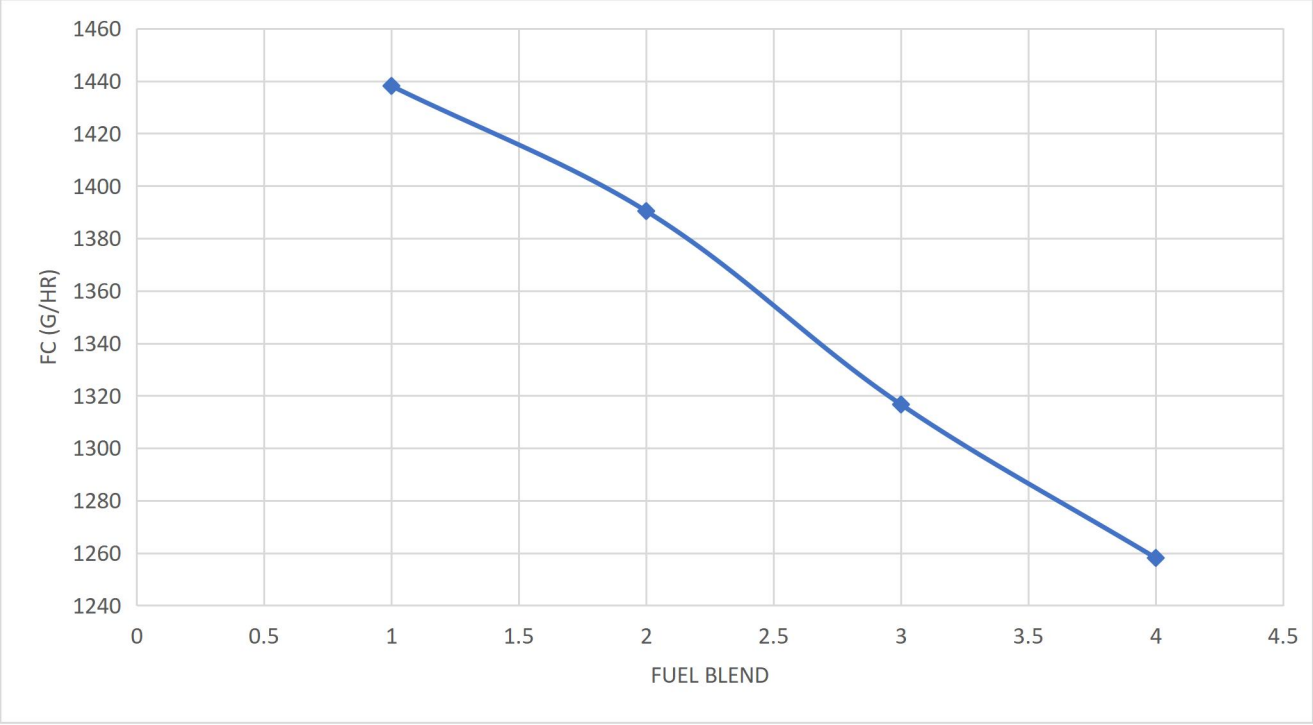


*Figure 4- 2: Effects of biodiesel blends on rate of fuel consumption*

### 4.6.3. Brake Specific Fuel Consumption (BSFC)

Brake Specific Fuel Consumption (BSFC), which represents the mass of fuel consumed per unit brake power, decreased steadily as biodiesel concentration increased. As shown in Figure 3, BSFC declined from 7.778 kg/kWh at B10 to 5.804 kg/kWh at B25, reflecting improved combustion and thermal efficiency. The B20 blend again emerged as the most efficient formulation, recording a BSFC of 6.120 kg/kWh, which indicates better fuel utilization and energy conversion efficiency compared to other blends. The reduction in BSFC for B20 is attributed to its optimal balance between oxygen content and fuel energy density, which enables near-complete combustion and minimizes unburned hydrocarbons. Beyond B20, however, higher biodiesel fractions such as B25 tend to exhibit diminishing efficiency due to increased viscosity and slightly lower calorific value (El-Salmawy et al., 2020).

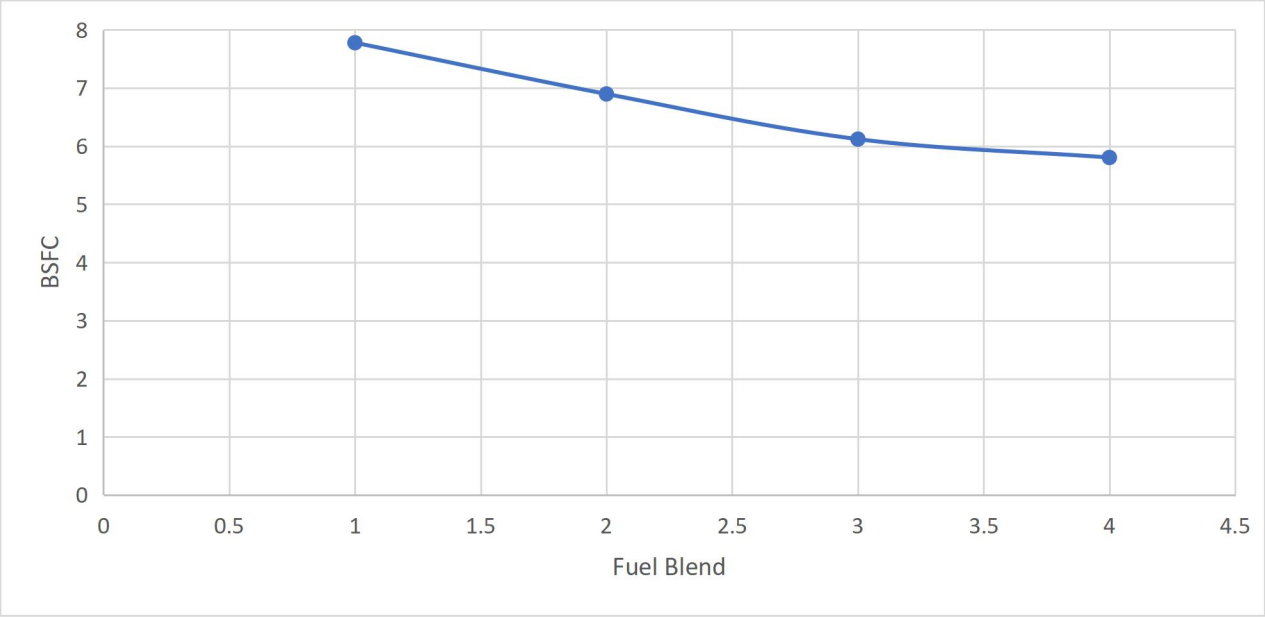


*Figure 4- 3: Effects of biodiesel blend on brake-specific fuel consumption*

### 4.6.4. Brake Thermal Efficiency (BTE)

Brake Thermal Efficiency (BTE) is a critical indicator of an engine's ability to convert the chemical energy of fuel into useful mechanical work. As presented in Figure 4, BTE showed a steady increase with rising biodiesel concentration, improving from 1.076% for B10 to 1.263% for B25. This progressive enhancement reflects the superior combustion characteristics of biodiesel, attributed to its intrinsic oxygen content, which promotes more complete oxidation of the fuel–air mixture and reduces energy losses during combustion (Oshomogho & Okologume, 2024).

Among the tested blends, the B20 blend exhibited the most favorable efficiency balance, achieving a BTE of 1.202%, which represents a notable improvement over lower blends while maintaining stable power output and fuel economy. This result aligns with the objective of identifying an optimal biodiesel–diesel ratio that improves energy conversion efficiency without imposing excessive fuel consumption or mechanical strain. The improved BTE at B20 can be explained by the synergistic balance between oxygen enhancement and calorific value retention, ensuring more effective energy release per unit mass of fuel compared to both lower and higher blends (Harari et al., 2019).

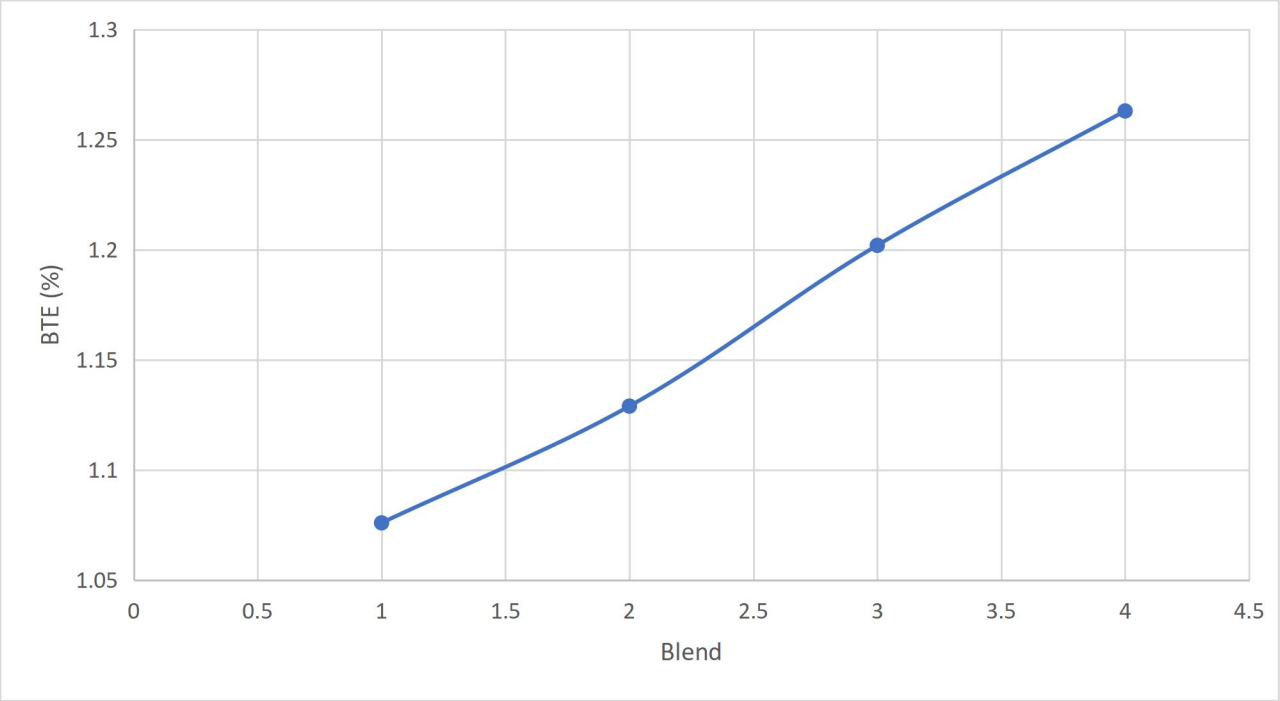


*Figure 4- 4: Break thermal efficiency of biodiesel blends*

The observed behavior corroborates the findings of Y. Chen et al. (2023), who reported that blending 5–20% biodiesel with conventional diesel improved thermal efficiency by 1–4%, with B20 achieving the highest gains due to optimal combustion temperature and improved fuel atomization. Similarly, Oshomogho & Okologume (2024) noted that moderate biodiesel blends enhance the utilization of thermal energy in the engine, leading to improved overall performance and energy efficiency. While BTE increased across all blends, the B20 blend emerged as the most technically efficient, providing an optimal trade-off between combustion completeness and fuel economy. This finding reinforces the suitability of B20 as the preferred WCO biodiesel blend for achieving high thermal efficiency and sustainable engine operation (Harari et al., 2019).

## CHAPTER FIVE

# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

The results of this study showed that the 20:80 biodiesel–petrol diesel blend demonstrated good physicochemical properties suitable for use as an alternative fuel. The measured density of 0.838 g/cm³ was within the acceptable range for diesel fuels, while the viscosity of 3.61 mpa.s indicated improved flow and atomization characteristics due to petrol dilution. The flash point of 62°C confirmed enhanced safety in handling and storage compared to pure vegetable oil. The acid value of 0.49 mg KOH/g and cetane number of 48.63 were within biodiesel standards, suggesting stable combustion quality and minimal deposit formation. Furthermore, the calorific value of 42.05 MJ/kg showed strong energy potential comparable to conventional diesel. These results collectively indicate that the 20% biodiesel and 80% petrol diesel blend exhibits favorable fuel characteristics that meet or approach ASTM biodiesel standards, confirming its technical feasibility as a renewable and cost-effective alternative fuel for compression ignition engines.

## 5.2. Recommendations

The following suggestions are recommended for future experimental work based on this study:

(i). Further optimization of the esterification and transesterification stages is recommended to reduce the FFA content of WCO below 2 wt.% and improve overall biodiesel yield and conversion efficiency.

(ii). Investigation into the influence of different blending ratios (beyond B25) on engine durability, performance, and long-term emission behavior should be undertaken.

(iii). Future work should focus on the development of cost-effective heterogeneous catalysts derived from waste materials (e.g., calcium phosphate scum) to enhance catalytic efficiency and reusability.

(iv). Optimization of methanol-to-oil molar ratios and reaction temperatures is necessary to reduce methanol consumption and improve process economics.

(v). Comprehensive engine emission and performance tests under variable loads and real driving conditions should be conducted to validate laboratory-scale findings.

(vi). Economic analysis and life-cycle assessment (LCA) should be performed to evaluate the sustainability and market competitiveness of large-scale WCO biodiesel production.

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## APPENDIXES

**Density:**

$$Density = \frac{Mass}{Volume}$$

Volume of density Bottle (V) = 50ml

Mass of density of empty bottle = 27.90g

Mass of density of bottle filled with oil = 74.45g

Mass of oil = mass of density bottle filled with oil – Mass of density of empty bottle

Mass of oil = 74.45g – 27.90g = 46.55g

$$Density = \frac{46.55}{50} = 0.931 g/ml$$

**Acid Value:**

$$Acid\ Value\ = \frac{N \times 56.1 \times (V_s - V_b)}{weight\ of\ oil\ of\ sample}$$

Sample titre value ($V_s$) = 1.9

Blank titre value ($V_b$) $= 0.1$

Mass of sample = 1g

$$Acid\ Value\ = \frac{0.05 \times 56.1 \times (1.9 - 0.1)}{1} = 5.049$$

Free Fatty Acid $(FFA) = \frac{Acid\ Value}{2} = \frac{5.049}{2} = 2.5245\ \%$

**Esterification:**

Total mass of oil = 1584.408g

Methanol content: 23% of the total weight of the oil which was measured for methanol and was added to the oil.

$$\frac{23}{100}\ (1584.408) = 364.41334g$$

Sulphuric Acid Content: 1% of the total weight of the oil which was measured for sulphuric acid and was added to the oil.

$$\frac{1}{100}\ (1584.408) = 15.84g$$

**Transesterification:**

After esterification the oil was filtered from the methanol and dissolved free fatty acid

Total mass of oil = 1651.934

We carried out Acid value test for the oil after esterification before transesterification

**Acid Value:**

$$Acid\ Value\ = \frac{N \times 56.1 \times (V_s - V_b)}{weight\ of\ oil\ of\ sample}$$

Sample titre value ($V_s$) = 0.4

Blank titre value ($V_b$) $= 0.1$

Mass of sample = 1g

$$Acid\ Value\ = \frac{0.05 \times 56.1 \times (0.4 - 0.1)}{1} = 0.84$$

Free Fatty Acid $(FFA) = \frac{Acid\ Value}{2} = \frac{0.84}{2} = 0.42\%$

Methanol content: 23% of the total weight of the oil which was measured for methanol and was added to the oil.

$$\frac{23}{100}\ (1651.934) = 379.94482g$$

Sodium hydroxide Content: 1% of the total weight of the oil which was measured for sulphuric acid and was added to the oil.

$$\frac{1}{100}\ (1651.934) = 16.51934g$$