TECHNOECONOMIC ANALYSIS OF BIODIESEL PRODUCTION BY ONE-POT TRANSESTERIFICATION OF A TERNARY BLEND OF NON-EDIBLE OILS

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CERTIFICATION

This is to certify that this research project, submitted to the Department of Chemical Engineering, was carried out by, ONIOVOSA ROYAL OKUYADE from the University of Benin, Benin City, Edo State, Nigeria, under the guidance of Engr. (Mrs.) Oiwoh.

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DEDICATION

This research project is dedicated to God Almighty, my creator and provider, in whose grace I scaled through and also my parents of inestimable value, whose encouragement and support has been my source of inspiration.

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There are not enough words to express my gratitude to God Almighty for being there for me throughout my stay in school. Much thanks to my ever darling and helpful parents, Mr. and Mrs. Oniovosa, for their encouragement and financial assistance throughout my stay.

This work is a result of many long hours involving intensive research and the culmination of a process that included the constant assistance and guidance afforded to me by my supervisor, ENGR. (MRS.) OIWOH, who patiently guided me and greatly enriched my knowledge. This achievement is being accomplished in no small measure due to her sheer professionalism. It is to him that I owe my heartfelt thanks and the overwhelming sense of satisfaction that I feel at this stage.

I would like to thank all the members of the Departmental laboratory who have contributed to making my stay very profitable and pleasant. All these thanks are however, only a fraction of what is due to God Almighty for granting me the opportunity and strength to successfully accomplish this assignment.

ABSTRACT

The growing demand for renewable and sustainable fuels has led to increased research into biodiesel production from non-edible oils. This study aims to evaluate the technoeconomic feasibility of biodiesel production from a ternary blend of neem oil, castor oil, and waste vegetable oil. The research focuses on analyzing the economic viability through Aspen Plus simulation, with an emphasis on optimizing reaction parameters to achieve a high biodiesel yield while maintaining cost-effectiveness.

In this study, the acid values of the feedstocks were first determined through titration, revealing the need for pre-treatment via esterification before transesterification. The Aspen Plus process simulation was employed to model the transesterification reaction, incorporating key factors such as methanol-to-oil ratio, reaction temperature, and the flowrate. A techno-economic analysis was conducted to determine capital investment, operating costs, net present value (NPV), internal rate of return (IRR), and payback period, providing insights into the financial viability of the biodiesel production process.

The results indicate that biodiesel production from the ternary blend is economically feasible. The total capital investment for the project was $7,020,220 (₦10,603,000,000), with an annual operating cost of $1,793,070 (₦2,710,000,000). The total revenue generated was $15,678,800 (₦23,678,000,000) per year, leading to an NPV of $78,295,380 (₦118,180,000,000) at a 10% interest rate. The internal rate of return (IRR) was 28.2%, demonstrating strong investment potential, while the payback period was approximately 0.51 years (~6 months), indicating rapid cost recovery. Additionally, the profit margin was 88.56%, confirming the economic viability of the process.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND TO THE STUDY

The increasing global demand for energy has placed immense pressure on natural resources, particularly fossil fuels, which are non-renewable and environmentally detrimental. Traditional energy sources like coal, oil, and gas have been the dominant drivers of industrial and economic development. However, their consumption leads to the release of significant amounts of greenhouse gases (GHGs), contributing to global warming and climate change (Dhurba, 2022). As of 2021, more than 80% of the world's energy is still derived from fossil fuels, with adverse effects on the environment (Fatih et al., 2021). This has led to a growing need to explore alternative and sustainable energy sources that reduce carbon footprints and promote environmental sustainability (Harish et al., 2020)

Among the many alternative energy sources being explored, biofuels have emerged as a potential solution to reduce dependency on fossil fuels while addressing environmental concerns (Tamás et al., 2021). Biofuels, specifically biodiesel, are produced from renewable resources such as vegetable oils, animal fats, and waste oils (Dhurba, 2022). Biodiesel has been recognized for its ability to reduce carbon emissions, improve air quality, and offer a sustainable solution to the energy crisis. Compared to conventional diesel, biodiesel is biodegradable, non-toxic, and produces fewer harmful emissions, including carbon monoxide (CO), sulfur oxides (SOx), and particulate matter (PM) (Muhammad et al., 2024).

However, the sustainability of biodiesel production largely depends on the feedstocks and catalysts used. Edible oils like soybean and palm oil have been widely used in biodiesel production, but concerns over food versus fuel competition have spurred interest in non-edible oils and waste materials. Non-edible oils like castor oil, neem oil, and waste vegetable oil (WVO) offer a more sustainable alternative because they do not compete with food crops and can be sourced from marginal lands unsuitable for food production (Chien et al., 2021). Additionally, the use of waste oils reduces the environmental impact of waste disposal, making the overall biodiesel production process more sustainable (Farayi et al., 2023).

Biodiesel production utilizes feedstocks from a wide range of sources, including non-edible options such as animal fats, used cooking oil, and oilseeds like castor, neem, and Jatropha oil, as well as edible oils like soybean, canola, palm, and sunflower. Emerging feedstocks like algae, which can efficiently produce lipid-rich oils, are also gaining attention. The unique physicochemical properties of each feedstock such as acid value, saponification value, and iodine value affect the yield, sustainability, and quality of biodiesel. While edible oils are known for their high yield and established extraction processes, concerns about food security have driven interest toward non-edible feedstocks and algae, which can be grown on marginal lands and offer environmental benefits. Optimizing the use of various feedstocks is critical for ensuring the sustainable production of biodiesel as a renewable energy source (Supriyanto et al., 2021).

Mixed feedstocks a combination of edible, non-edible, and waste oils are increasingly being explored as a way to optimize the cost and yield of biodiesel production. For example, blending castor oil, which has high viscosity, with waste vegetable oil can enhance the cold flow properties of biodiesel while keeping production costs low. Research shows that mixed feedstocks provide a

balanced solution by utilizing the strengths of each feedstock, improving biodiesel yield and quality (Sharma et al., 2022).

Another important factor in biodiesel production is the catalyst used in the transesterification reaction, which converts oils into biodiesel. Traditional homogeneous catalysts like sodium hydroxide (NaOH) and potassium hydroxide (KOH) have been widely used, but they present challenges such as soap formation, toxic waste, and corrosion (Ude et al., 2022). As a result, researchers are turning to heterogeneous catalysts derived from non-traditional sources, such as anthill soil, cow horn ash, and pawpaw stem ash. These catalysts are more environmentally friendly, easier to recover, and can be reused in multiple production cycles, reducing production costs and waste (Ude et al., 2021).

1.2 STATEMENT OF THE PROBLEM

The increasing demand for sustainable energy sources has intensified the exploration of biodiesel production as a viable alternative to fossil fuels. However, traditional biodiesel production methods often rely on costly catalysts and feedstocks, which limits their economic feasibility and accessibility, particularly in developing countries like Nigeria. The use of non-traditional catalysts such as anthill, pawpaw stem, and cow horn has not been extensively studied, leaving a gap in knowledge regarding their efficiency and cost-effectiveness in biodiesel production.

Additionally, the mixed use of feedstocks, including castor oil, Neem oil, and waste vegetable oil, presents an opportunity to enhance the yield and reduce production costs. However, the economic implications of utilizing these alternative catalysts and mixed feedstocks remain largely unexamined. The lack of comprehensive research on the production processes, cost analysis, and

potential environmental benefits poses significant challenges for stakeholders in the energy sector, policymakers, and researchers.

Furthermore, there is an urgent need to address the environmental issues associated with waste vegetable oil disposal and the depletion of traditional fossil fuel sources. This study aims to fill the gap by analyzing the economic feasibility and cost implications of biodiesel production using these innovative catalysts and feedstocks, thereby contributing to sustainable energy solutions and promoting waste utilization practices.

1.3 AIM AND OBJECTIVES OF THE STUDY

The aim of this study is to carry out technoeconomic analysis of biodiesel production by one-pot transesterification of a ternary blend of non-edible oils.

The objectives of this study are;

1. Characterization of oils using suitable characterization techniques to determine their suitability for biodiesel production.

2. Conduct a technoeconomic assessment, evaluating capital investment, operating costs, net present value (NPV), internal rate of return (IRR), and payback period, to determine the economic feasibility of the production process.

1.4 SCOPE OF THE STUDY

This study focuses on the production of biodiesel using non-traditional catalysts and mixed feedstocks, specifically castor oil, neem oil, and waste vegetable oil. The research involves a laboratory-based investigation where various experiments will be conducted to evaluate the

efficiency of the selected catalysts in the transesterification process. Additionally, a technoeconomic analysis of the transesterification reaction of a ternary blend of non-edible oils using a composite heterogeneous catalyst will be performed. Aspen Plus simulation software will be utilized to assess the economic feasibility of the process, providing insights into the cost-effectiveness and overall sustainability of biodiesel production.

It is important to note that this study will not address broader issues related to national energy policies or the commercialization of biodiesel but will focus specifically on the laboratory-scale production processes and their associated economic and environmental assessments.

1.5 SIGNIFICANCE OF THE STUDY

By exploring the use of non-traditional catalysts and mixed feedstocks for biodiesel production, this research contributes to the development of sustainable energy solutions that can reduce reliance on fossil fuels, thereby supporting global efforts to combat climate change and promote renewable energy sources.

Through a comprehensive economic analysis, the study also provides insights into the cost-effectiveness of using non-traditional catalysts in biodiesel production. This can guide policymakers, entrepreneurs, and investors in making informed decisions regarding investment in biodiesel production technology and the potential for job creation in the renewable energy sector.

In general, the use of non-traditional catalysts and mixed feedstocks for biodiesel production enhances the economic viability and sustainability of renewable energy sources. By minimizing operational costs and environmental impacts, this research not only supports the growth of the biodiesel industry but also promotes energy security and environmental health. Ultimately, the

findings of this study could lead to more robust policies and practices that favor the development of green energy solutions, benefiting both local communities and the global environment.

CHAPTER TWO

LITERATURE REVIEW

2.1 ENERGY IN NIGERIA

Nigeria is richly endowed with diverse energy resources, including fossil fuels such as crude oil, natural gas, and coal, as well as renewable energy sources like solar, wind, hydropower, and biomass. Additionally, the country has access to alternative fuels like biofuels. However, despite this abundance, Nigeria struggles to utilize these resources effectively to meet its increasing energy and electricity demands. Fossil fuels dominate the country's energy production and exports, with crude oil and natural gas contributing over 90% of national revenue (Adewuyi et al., 2020).

The energy sector faces numerous challenges, such as inadequate infrastructure, limited electricity access in rural areas, frequent power outages, and a heavy dependence on conventional energy sources. As one of the world's leading petroleum producers and exporters, Nigeria's oil and gas sector accounted for 75% of public revenue and 86% of export revenue in 2019. A significant portion of these earnings has been allocated to subsidizing fossil fuels, including petrol (PMS). Despite its status as Africa's largest oil producer, Nigeria still imports a substantial portion of its domestic oil needs. In 2017, domestic energy consumption was approximately 1.54 quadrillion British thermal units (BTU), representing just 0.26% of global energy use, while the country's energy production reached 5.95 quadrillion BTUs, exceeding its consumption by 386%. The surplus energy is often exported to neighboring countries, creating additional challenges for regional energy growth (Obeagu & Owunna, 2022).

However, Nigeria's energy resources are increasingly unable to meet its growing demands due to several factors, including inadequate infrastructure, industrial expansion, rapid population growth,

global climate change, and the environmental impacts of fossil fuel use. As a result, households and businesses now face significant energy shortages. To address these issues, Nigeria is actively exploring sustainable, eco-friendly energy alternatives, with a focus on renewable resources (Owunna & Obeagu, 2022).

2.2. BIOFUELS

Fuels are essential for modern-day living, playing a critical role in activities ranging from basic cooking to operating heavy machinery. The primary demand for fuels is largely met by fossil fuels (Biswajit Nath et al., 2019). Society relies heavily on fuel for its continuity and advancement. However, with the steady increase in energy consumption, fossil fuels are projected to deplete. Current estimates suggest that petroleum shortages may occur between 2070 and 2080 (Singh. et al., 2020). In light of this worsening situation, scientists are actively exploring and developing alternative energy sources that prioritize renewability and environmental sustainability. Efforts are being made to enhance the utilization of renewable energy resources such as solar, wind, hydro, ocean, and tidal energy. Despite these efforts, none of these options fully satisfy the requirements to replace conventional fossil fuels. Therefore, the development of a viable green renewable fuel is urgently needed to address the current challenges.

Biofuels are energy-rich compounds derived from plant- and microbe-based biomass through various biochemical, physical, and thermochemical processes. They are considered a practical substitute for fossil fuels and are applicable in transportation, industrial, residential, commercial, and power-generation sectors. Unlike nonrenewable energy sources, biofuels offer numerous benefits, including energy security, reduced greenhouse gas emissions, economic growth, and

support for rural livelihoods by creating jobs and market opportunities for domestic crops (Anshu Priya et al., 2023).

Biofuels such as bioethanol, biodiesel, and biogas have emerged as promising solutions to meet future energy demands (Sujata Brahma et al., 2022). They are classified into four generations based on their feedstock or biosynthetic platform, such as genetic engineering. This essay discusses the advantages and disadvantages of these biofuel categories compared to fossil fuels. The progress of biofuel technologies also depends on socioeconomic and political factors, which can benefit significantly from policy recommendations by regulatory authorities (Philipp Cavelius et al., 2023).

First-generation biofuels primarily include bioethanol and biodiesel. First-generation bioethanol is produced via microbial fermentation of edible feedstocks rich in starch and sucrose, such as wheat, corn, and sugarcane, commonly used in Europe, North America, and South America, respectively (Philipp Cavelius et al., 2023). However, bioethanol production is not confined to the first generation; it can also belong to the second or third generation depending on the feedstock and production strain (Tse TJ. et al., 2021).

Second-generation biofuels were developed to address some of the challenges associated with first-generation biofuels. They utilize lignocellulosic biomass from agricultural and forest residues, as well as other waste streams such as wheat bran, animal fats, or used cooking oil from the food industry. Non-food plants like Jatropha curcas, a drought-resistant shrub that can grow on wastelands, also serve as promising sources for second-generation biofuels. These biofuels avoid the need for agricultural land-use changes and do not compete with food supplies. However, second-generation feedstocks are often more complex than those used in the first generation, containing compounds like lignin that can hinder fermentation efficiency. As a result, additional

pretreatment steps are often required, increasing both process time and costs (Malode SJ. et al., 2021).

Third-generation biofuels are primarily derived from microalgae and cyanobacteria biomass, which can naturally produce alcohols and lipids for conversion into biodiesel or other high-energy fuel products (Philipp Cavelius et al., 2023).

To overcome the limitations of first, second, and third-generation biofuels, fourth-generation biofuels are being developed using advanced techniques such as co-culturing, nanotechnology, and genetically modified organisms. These advancements aim to establish a circular bioeconomic system, paving the way for sustainable development in the fuel industry (Lubhan Cherwoo et al., 2023).

2.2.1 BIOETHANOL

Bioethanol derived from biological resources is recognized as a renewable, sustainable energy source and a viable alternative within the framework of the circular economy. It offers an energy content comparable to gasoline but emits fewer harmful pollutants than fossil fuels. However, bioethanol must be dehydrated to blend with standard gasoline for use as vehicle fuel (Samira Karimi et al., 2021).

Currently, bioethanol is being explored as a substitute for traditional gasoline due to its comparable properties and advantages, such as reducing greenhouse gas emissions and extending fuel reserves. Commercial bioethanol production predominantly relies on edible feedstocks like corn and sugarcane, which increases production costs. These high costs have driven the search for second- and third-generation (3G) bioethanol, produced from more affordable and readily available

feedstocks. Fourth-generation bioethanol is now under development to further enhance the capabilities of algae in capturing CO2 and improving the production of specific compounds. Despite these advancements, the cost of processing non-edible feedstocks remains a significant challenge, preventing bioethanol from being cost-competitive with conventional gasoline (Ifeanyichukwu Edeh, 2021).

Traditional alcoholic fermentation processes for first-generation bioethanol have utilized food crops such as wheat, corn, potatoes, beets, and sugarcane because of their high starch and sugar content, which are ideal for fermentation. However, with increasing global population and limited arable land, concerns have arisen regarding the use of food crops for fuel production. As a result, non-edible biomass sources, including lignocellulosic materials and algae, are being investigated as sustainable alternatives for bioethanol production (Timothy J.Tse et al., 2023).

2.2.2 BIOGAS

Biogas is a combustible gas generated through the anaerobic digestion of organic materials. It primarily consists of 60–70% methane and 30–40% carbon dioxide, along with trace amounts of other gases such as hydrogen, nitrogen, oxygen, carbon monoxide, and hydrogen sulfide. The composition of biogas depends on factors like the raw materials used, the temperature within the reactor, and the retention time of the materials in the fermentation tank. A higher carbon dioxide content in biogas significantly reduces its heating value and flammability. Therefore, upgrading biogas by removing CO2 is essential to enhance its energy content (Thanigaivel et al., 2022).

Biogas is a sustainable, cost-effective, and competitive energy source, given the plentiful availability of low-cost feedstocks and its diverse applications in heating, power generation, fuel production, and the manufacture of sustainable chemicals like hydrogen and carbon dioxide. The

global capacity for biogas-based power has grown rapidly over the past decade, with electricity generation capacity increasing from 65 GW in 2010 to 120 GW in 2019, marking a 90% growth (Moses Jeremiah and Oludolapo Akanni, 2022).

Biogas serves multiple purposes, including heat and electricity generation, as well as acting as a raw material for producing biofuels, biomethane, carbon dioxide, and hydrogen (Prussi M. et al., 2019). Biogas production is regarded as a highly promising and eco-friendly alternative to fossil fuels. Among various renewable energy sources, biogas holds a unique position due to the abundant availability of biomass and the critical need to manage agricultural and commercial waste (Katarzyna Ignatowicz et al., 2023).

2.2.3 BIODIESEL

Biodiesel is a mono-alkyl ester derived from renewable lipid sources such as vegetable oils, waste cooking oil, microalgae, and animal fats, containing fatty acids like C12, C14, C16, C18, and C22 (G.M. Kalu-Uka et al., 2021).

Greenhouse gas (GHG) emissions, which contribute to global warming and climate change, are among the most pressing environmental challenges of the 21st century. With industries relying heavily on power plants and society's dependence on transportation and fossil fuel-based products, researchers are actively exploring alternative energy sources (Arman Amani Babadi et al., 2022).

Biodiesel, also referred to as fatty acid methyl esters (FAME), has been globally studied as a renewable fuel alternative to address transportation energy needs and reduce GHG emissions. This biodiesel is produced through the transesterification of fats and oils with methanol. Life cycle

assessments indicate that using biodiesel can lower carbon dioxide (CO2) and carbon monoxide (CO) emissions by 8–41% (N. Mahbub et al., 2019).

Biodiesel can be produced from various renewable resources, including waste cooking oil (S.S. Bargole et al., 2021), vegetable seed oils (T. ShenavaeiZare et al., 2021), animal fat, and microalgal oils. Its use in internal combustion engines dates back to the early 19th century. Biodiesel is sulfur-free, non-toxic, biodegradable, and provides superior lubrication compared to petroleum diesel. Additionally, modern diesel engines can utilize biodiesel without requiring any modifications (Arman Amani Babadi et al., 2022).

Countries lacking crude oil reserves have decreased their dependence on oil imports by developing local biodiesel production and supply chains (Rahman et al., 2021). However, the widespread adoption of biodiesel is limited by high production costs and competition with food resources. Feedstock accounts for 70–85% of the total production cost, while catalyst expenses, energy usage, and purification processes contribute an additional 15–30% (E.K. Sitepu et al., 2020).

Despite these challenges, biodiesel remains a promising alternative fuel with significant potential to reduce carbon footprints, support energy diversification, expand agricultural economies, and minimize pollution. Although its current cost is 1.5–3 times that of fossil diesel in advanced economies, production is expected to grow in the coming years due to its numerous environmental and economic benefits (G.M. Mathew et al., 2021).

2.3 BIODIESEL PRODUCTION METHODS

There are four primary methods by which raw feedstocks can be processed to serve as alternative fuels for diesel engines. These methods aim to reduce the viscosity of the oil, enhance its oxidation stability, and improve its volatility, ensuring it meets the standards for biodiesel usage.

2.3.1 DIRECT BLENDING OF OILS

Direct blending involves diluting raw oil feedstocks with petroleum diesel to reduce their viscosity. This process is essential because the viscosity of crude vegetable oil is approximately 10–17 times higher than that of petroleum diesel, which affects its suitability as a fuel.

2.3.2 MICRO-EMULSION OF OILS

The micro-emulsion method mixes oil feedstocks with appropriate solvents to enhance their properties. Common solvents used in this process include methanol, ethanol, and 1-butanol (M. Ndiaye et al., 2020). To address the limited solubility of alcohols, amphiphilic compounds such as phospholipids, sorbitan monooleate, n-butanol, 2-octanol, and carboxylate surfactants are used to stabilize the mixture and improve solubility. This technique results in fuel emulsions that emit fewer pollutants, such as nitric oxide and carbon monoxide, compared to unblended vegetable oil or pure diesel (Arman Amani Babadi et al., 2022).

2.3.3 THERMAL CRACKING (PYROLYSIS) OF OILS

Thermal cracking, or pyrolysis, involves the breakdown of large organic molecules into smaller ones by applying heat in the absence of air or oxygen. This approach is an alternative method for biodiesel production (Pan X. et al., 2020). Pyrolysis processes can be categorized into catalytic and non-catalytic methods, with silica-alumina and zeolite being commonly used catalysts.

However, thermal cracking has certain limitations, including high equipment costs and the need for oxygen removal. Additionally, the process often leads to incomplete conversion of the oil, yields few environmental benefits, and generates low-value by-products (Arman Amani Babadi et al., 2022).

2.3.4 TRANSESTERIFICATION

In this study, the transesterification process will be employed. Transesterification is a chemical reaction between alcohol and lipids that results in the formation of fatty acid alkyl esters (FAAE). During this process, triglycerides react with alcohol to produce FAAE and glycerol. Initially, triglycerides and alcohol combine to form diglycerides, which are subsequently converted into monoglycerides and glycerol, with each step yielding alkyl esters (Thangaraj et al., 2019).

Several factors impact the biodiesel yield in transesterification, including reaction time, temperature, catalyst type and concentration, feedstock oil type, and the alcohol-to-oil ratio. The process can also be reversed; thus, to favor the production of biodiesel, an excess amount of alcohol is required to shift the reaction equilibrium. Various types of alcohols, including short-chain, long-chain, and cyclic alcohols, are used in this process. However, methanol and ethanol are the most commonly used due to their availability, polarity, high reactivity, and affordability (Sabah Mohamed Farouk et al., 2024).

Biodiesel is produced through a chemical process called transesterification, in which triglycerides are sequentially converted into diglycerides, monoglycerides, and ultimately glycerol. This process typically employs alkali catalysts in a single-phase reaction. However, when the feedstock contains high levels of water or free fatty acids (FFAs), a two-step process may be necessary. The

first step, acid-catalyzed alcoholysis, converts FFAs into fatty acid esters, followed by transesterification to transform these esters into biodiesel (Sabah Mohamed Farouk et al., 2024).

Methanol and ethanol are the most commonly used alcohols in this process due to their short chain lengths, affordability, and high reactivity with triglycerides in the feedstock. To drive the reversible transesterification reaction toward biodiesel production, an excess amount of methanol is often required. The by-product of this process, glycerol, has practical applications such as soap production. The reaction can be catalyzed using alkaline, acidic, or biological catalysts (S. Brahma et al., 2022).

2.4. OILS USED IN BIODIESEL PRODUCTION

Biodiesel production utilizes a wide variety of oils, which are classified into two main categories: first-generation feedstocks (edible oils) and second-generation feedstocks (non-edible oils). These feedstocks differ in terms of cost, availability, sustainability, and environmental impact, with each offering unique advantages and limitations for biodiesel production.

The choice of primary biodiesel feedstock varies by country, depending on climate, environmental factors, and dominant agricultural products (M. Rouhany and Montgomery, 2019). For instance, Canada primarily uses canola, the United States relies on soybeans, Malaysia produces biodiesel from palm oil, and Nigeria focuses on Jatropha curcas (M.A. Oluleye et al., 2019). In Europe, rapeseed oil and corn oil are commonly used. Globally, Indonesia and the United States were among the leading biodiesel producers in 2019, with outputs of 7.9 billion liters and 6.5 billion liters, respectively (Fig. 1). The United States is projected to produce over 1 billion gallons of biodiesel by 2025, a growth trend that began after the Energy Policy Act of 2005, which introduced tax incentives for certain energy sources (REN21 2021).

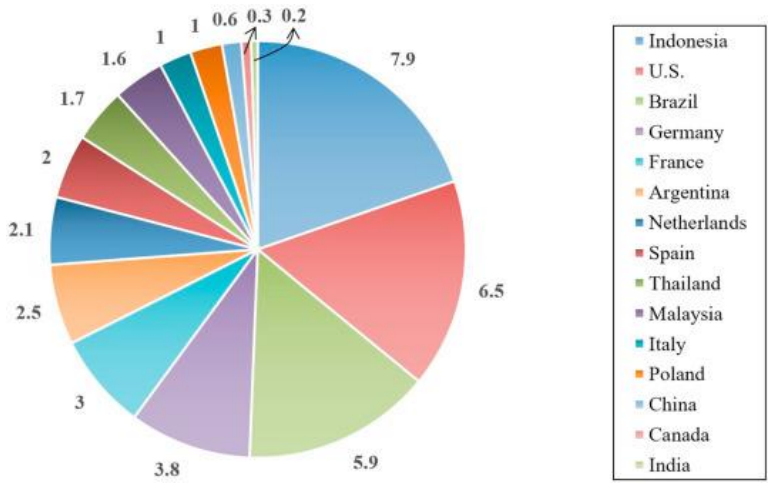

Figure 2. 1 Global biodiesel production by country in 2019 (biodiesel production in billion liters) (REN21 2021).

The selection of biodiesel feedstock is typically influenced by the climate conditions of a given country. Choosing the appropriate feedstock plays a crucial role in reducing production costs. A key component of feedstock is free fatty acid (FFA), which is converted into biodiesel during the production process. However, an excessive amount of FFA can disrupt production by causing issues such as soap formation (L. di Bitonto et al., 2020). Feedstocks can also be categorized based on their FFA content: Group 1 includes feedstocks with approximately 1.5% FFA (e.g., soybean, canola, and palm oil); Group 2 has FFA levels below 4% (e.g., cooking oils, tallow, and poultry fat); and Group 3 comprises feedstocks with over 20% FFA (e.g., animal fats and greases) (A. Gaurav et al., 2019). Feedstocks with FFA levels below 2.5 wt% are considered ideal for biodiesel production, as higher FFA content typically requires pretreatment, increasing production costs. Biodiesel feedstocks are generally grouped into three main generations.

2.4.1 FIRST-GENERATION FEEDSTOCKS (EDIBLE OILS)

First-generation feedstocks are derived from edible oils such as soybean, sunflower, palm, canola, and coconut oils. These oils are widely favored due to their ease of processing and high biodiesel

yield. Biodiesel produced from first-generation feedstocks can be blended with petroleum-based fuels or used independently in diesel engines (K. Viswanathan et al., 2021). The production process typically involves transesterification, where triglycerides react with alcohol in the presence of a catalyst to produce fatty acid methyl esters (FAME) and glycerol.

Edible oils offer advantages like high oil content and well-established processing techniques. Soybean and palm oils are particularly popular due to their abundance and relatively high oil output. However, their use in biodiesel production has raised concerns about sustainability, including the food versus fuel debate. Other issues include water scarcity, soil degradation, deforestation, and biodiversity loss (Arman Amani Babadi et al., 2022).

2.4.2 SECOND-GENERATION FEEDSTOCKS (NON-EDIBLE OILS)

The non-edible oil crops, animal fats, whole plant tissue, agricultural remains, and wood residual wastage can be categorized into the second generation. To address the environmental and economic drawbacks of edible oils, researchers have turned to second-generation feedstocks, which include non-edible oils like Jatropha sp., Madhuca longifolia, salmon oil, tobacco seed, jojoba oil, sea mango, waste cooking oils, beef tallow, and pork lard (D. Singh et al., 2021). These oils are derived from plants not used for food, making them more sustainable options that do not compete with food supplies. Non-edible oils can be grown on marginal lands unsuitable for food crops, which helps avoid deforestation and maintains biodiversity.

Processing non-edible oils is more complex due to their high free fatty acid (FFA) content, which can cause soap formation during alkaline-catalyzed transesterification. This issue often necessitates an acid-catalyzed pre-treatment to lower FFA levels. Oils like Jatropha and castor have gained attention for their resilience to varying climates and ability to grow in poor soils,

making them ideal for biodiesel production in regions with limited resources. Compared to first-generation feedstocks, second-generation alternatives offer benefits such as higher efficiency, reduced land requirements, no food security issues, renewable properties, and non-corrosive fuel production with a high-octane number (D. Pagani, 2021).

However, the high concentration of saturated fatty acids in animal fats poses challenges for transesterification, as these fats are solid and require preheating to approximately 45°C. Despite this, the high saturated fat content results in biodiesel with greater stability and a higher cetane number (F. Toldra-Reig et al., 2020).

2.4.3 THIRD-GENERATION FEEDSTOCKS (ALGAL OILS)

Algal oils represent a promising third-generation biodiesel feedstock. These include oils from autotrophic and heterotrophic microalgae, yeasts, fungi, and bacteria. Algae are particularly advantageous due to their ability to produce significantly higher oil yields per hectare compared to traditional crops. They can also be cultivated in saline water, wastewater, or controlled systems, avoiding competition with food production.

Microalgae can produce up to four types of biofuels: biohydrogen (via direct photoproduction), methane (through anaerobic digestion), crude bio-oil (via thermochemical conversion), and biodiesel (extracted from microalgal oil) (B. Barati et al., 2021). Their high lipid productivity (30%–70% of dry weight) and potential applications in wastewater treatment make them environmentally favorable. Moreover, algae bypass the food versus fuel debate, making them a sustainable alternative to terrestrial crops (Zhao et al., 2021).

In summary, third-generation feedstocks like microalgae hold immense potential due to their efficiency, environmental benefits, and ability to coexist with food production systems. These attributes position algal oils as a leading candidate for future biodiesel production.

2.5 CATALYSTS IN BIODIESEL PRODUCTION

Catalysts are essential in biodiesel production, as they accelerate the reaction between oils/fats and alcohol to form biodiesel, also known as fatty acid methyl esters (FAME), and glycerol. The choice of catalyst significantly impacts the efficiency of the process, influencing reaction speed, product yield, and by-product formation. Catalysts used in biodiesel production are broadly classified into homogeneous and heterogeneous types, each with distinct benefits and limitations.

2.5.1 HOMOGENEOUS CATALYSTS

Homogeneous catalysts operate in the same phase (liquid or gas) as the reactants, typically dissolving in the reaction medium. Common examples include acid catalysts such as sulfuric acid (H_2SO_4) and hydrochloric acid (HCl), as well as base catalysts like sodium hydroxide (NaOH) and potassium hydroxide (KOH). These catalysts are widely used in industrial biodiesel production due to their simplicity and rapid reaction rates.

Homogeneous acid catalysts are particularly effective for feedstocks with high free fatty acid (FFA) content, whereas base catalysts are preferred for low-FFA feedstocks. However, their use poses challenges. Homogeneous catalysts are not reusable or regenerable, making their separation from the final product complex and costly. They are partially soluble in biodiesel and fully soluble in glycerol, requiring additional equipment and processes to separate them from the products, increasing production costs.

Acid catalysts, while offering slightly higher biodiesel yields than base catalysts, require extensive washing to remove residues, which can lead to equipment corrosion and increased water usage. On the other hand, base catalysts are prone to saponification, leading to soap formation that reduces FAME yield and complicates subsequent purification steps, including glycerol separation and water washing (Baohua Wang et al., 2023). Despite these drawbacks, homogeneous catalysts remain a staple in biodiesel production due to their high efficiency.

2.5.2 HETEROGENEOUS CATALYSTS

Heterogeneous catalysts are solid materials that operate in a different phase than the reactants, making them more suitable for continuous biodiesel production processes. They offer advantages such as high activity, selectivity, easy separation from products, and reusability (Faruque, M.O et al., 2020). Examples include base metal oxi des, metal carbonates or hydro carbonates, anionic resins, and basic zeolites (Hamza, M et al., 2021).

Heterogeneous catalysts generally require more demanding operating conditions, including higher temperatures, pressures, and alcohol-to-oil molar ratios. While conventional heterogeneous catalysts may perform less efficiently than homogeneous ones, advancements in catalyst design have produced solid catalysts capable of matching or exceeding their homogeneous counterparts. Furthermore, the purification of biodiesel produced with heterogeneous catalysts is simpler, as they do not require water washing, reducing operational complexity and waste generation (Vásquez Céspedes et al., 2021).

Innovations in nano catalysts and magnetic catalysts have further enhanced biodiesel yield and catalyst recyclability, outperforming traditional solid acid-base catalysts. However, heterogeneous catalysts are not without limitations. They are susceptible to poisoning, especially when processing

used cooking oils, and leaching, which contaminates the product and increases operational costs due to frequent catalyst replacement (Baohua Wang et al., 2023).

2.5.3 BI-FUNCTIONAL CATALYSTS (ACID AND BASE)

Bi-functional catalysts combine both acidic and basic active sites, enabling them to efficiently catalyze the transesterification of triglycerides and the esterification of free fatty acids (FFAs) without the need for a pre-treatment step to remove FFAs. This dual functionality makes them particularly useful for biodiesel production from low-quality feedstocks with high FFA content, such as waste oils and animal fats. By integrating both acid and base sites, bi-functional catalysts can simultaneously catalyze the esterification of FFAs and transesterification of triglycerides, leading to biodiesel production with minimal soap formation (Gourich et al., 2022).

These catalysts, with both acid and base sites, can simultaneously perform esterification and transesterification (F. Javed et al., 2022). This eliminates the need to separate products from the two processes and helps avoid saponification. An effective bi-functional catalyst, such as an amphoteric material, can be modified to enhance its performance. For example, zirconium oxide (ZrO_2) can be treated with lanthanum oxide (La_2O_3) or calcium oxide (CaO) to create acidic sites. Additionally, bi-functional catalysts naturally occur in the form of zwitterions, which are molecules with both positive and negative charges on different atoms, resulting in a neutral charge overall. Amino acids are a common example of zwitterions (Leiske MN et al., 2022). In this study, strontium zirconium oxide (7% Sr/ZrO_2) was produced as a heterogeneous catalyst for biodiesel synthesis and compared with zwitterions for overall conversion and reaction rate.

Bi-functional catalysts can simplify the downstream processing of biodiesel by avoiding saponification issues. However, esterification with these catalysts may still exhibit slow kinetics

due to poor reactant miscibility and the establishment of thermodynamic equilibrium, which results from water production as a by-product. Several strategies, such as reactive distillation and optimized reactor configurations, have been proposed to overcome these challenges (Maina et al., 2023).

2.6 ECONOMIC FEASIBILITY AND COST ANALYSIS OF BIODIESEL PRODUCTION

The economic feasibility of biodiesel production is primarily determined by feedstock costs, which can account for up to 80% of the total production expenses. While edible oils like soybean and rapeseed are common feedstocks, they are also among the most expensive, raising concerns about the economic viability of biodiesel, especially in regions where these oils are essential for food. For example, research indicates that in areas with high demand for soybean oil as a food source, biodiesel production from soybean oil may not be financially competitive without substantial subsidies or support programs.

However, the increasing demand for oil faces two major challenges: resource scarcity and the negative environmental impact of its use. These issues highlight the need for alternative and more sustainable fuels, prompting increased research into alternative energy sources. Biodiesel, produced from a variety of feedstocks including waste products such as used cooking oil, oily sludge from factories, and animal fats has gained significant attention as a viable alternative. Moreover, various technological approaches to biodiesel production, based on feedstock quality, provide opportunities to reduce overall production costs (S.N. Gebremariam and J.M. Marchetti, 2018).

The primary challenges of biodiesel as a fuel include its higher production costs, lower energy content compared to fossil diesel, and nitrogen oxide emissions upon combustion. However, it is typically the high production cost that limits its widespread adoption. In summary, three approaches can help reduce biodiesel production costs: improving production technologies for better yield, lowering capital costs, and reducing raw material costs, with feedstock costs being the most significant factor (S.N. Gebremariam and J.M. Marchetti, 2018).

Researchers have proposed several solutions to address the challenges of biodiesel production costs and the large-scale use of single oil feedstocks. One approach is blending oils in appropriate ratios before transesterification, which can help manage feedstock shortages and improve the quality of low-grade fuels (S. Kumar et al., 2021). The use of waste feedstocks, such as fruit and vegetable scraps offers a sustainable option that can substantially lower manufacturing costs.

Additionally, using waste feedstocks like used cooking oil and animal fats presents both economic and environmental advantages. Waste oils are typically less expensive than virgin edible oils, and utilizing these resources reduces disposal costs and environmental pollution

CHAPTER THREE

MATERIAL AND METHOD

This chapter describes the materials and methods used in the technoeconomic analysis of the transesterification reaction of a ternary blend of non-edible oils using a composite heterogeneous catalyst. The study employs Aspen Plus to simulate the biodiesel production process, comparing the performance of heterogeneous and homogeneous catalysts. The experimental design, reaction setup, simulation parameters, and economic evaluation methods are outlined in detail.

3.1 RAW MATERIALS AND REAGENTS

Table 3. 1: Apparatus and Equipment

Materials	Source	Use
Castor Oil	Castor was obtained from local vendor	Used for biodiesel production
Waste Cooking Oil (WCO)	WCO was sourced from restaurants	Used for biodiesel production
Neem Oil	Neem Was obtained from local vendor	Used for biodiesel production
Ethanol	Was obtained from local vendor	Used for acid and saponification value test
Deionized Water	Was obtained from laboratory vendor	Used for chemical reaction, solution preparation and

		laboratory equipment maintenance
Benzene	Was sourced from local vendor	Used for acid value test
Potassium hydroxide solution (KOH)	Was sourced from local vendor	Used for acid value test, saponification value test and homogeneous catalyst for biodiesel production
Hydrochloric Acid (HCl)	Was sourced from local vendor	Used for saponification value test
Phenolphthalein	Was sourced from local vendor	Used as indicator
Methanol	Was sourced from local vendor	Used for biodiesel production
Tetraoxosulphate(VI) Acid (H2SO4)	Was obtained from laboratory vendor	Used for esterification of oil

3.2 APPARATUS AND EQUIPMENTS

Table 3. 2: Apparatus and Equipment

Apparatus	Source	Use
250ml Beakers	Was purchased from local vendor	Used for holding, mixing, and heating reagents or samples.
Separating funnel	Was purchased from local vendor	Used to separate biodiesel from glycerol.
250ml Conical flask	Was purchased from local vendor	Used for mixing and heating solutions and oil samples.
Round bottom flask	Was purchased from local vendor	Used to hold oil samples for heating during characterization.
Reflux Condenser	Was sourced from Chemical Engineering Laboratory, UNIBEN	Used to maintain reaction temperature.
100ml Measuring Cylinders	Was purchased from local vendor	Used to measure the required volume of samples or reagents.
Retort stand	Was obtained from Chemical Engineering Laboratory, UNIBEN	Used to support the burette during titration.

Plastic funnel	Was purchased from local vendor	Used to convey reagents or solutions into burette
Burette	Was sourced from Chemical Engineering Laboratory, UNIBEN	Used to measure out the volume required for titration.
Laboratory measurement scale	Was obtained from Chemical Engineering Laboratory, UNIBEN	Used to measure the mass of oil samples and reagents.
Dropper	Was purchased from local vendor	Used to introduce indicator to the reaction mix in drops.
Hand gloves	Was purchased from local vendor	Used to protect hands from corrosive substances
Face mask	Was purchased from local vendor	Used to protect nose from dust or irritating substances
Filter Paper	Was purchased from local vendor	Used to filter impurities from oil samples.

3.3 METHODOLOGY

3.3.1 FEEDSTOCKS COLLECTION AND PREPARATION

One liter each of castor and neem oils was gotten from a local supplier while a restaurant supplied one liter of used cooking oil. Each oil was stored separately in an airtight container. The waste cooking oil was filtered through a muslin cloth to eliminate impurities.

3.3.2. FEEDSTOCK CHARACTERIZATION

Oil characterization plays a crucial role in ensuring quality control, product development, process optimization, performance assessment, and resolving issues related to oil properties and composition.

The characterization of the oils was conducted through the following tests, with all procedures adapted from existing literature:

1. Acid Value Test
2. Saponification Value Test
3. Density Test
4. Viscosity Test

3.3.2.1. ACID VALUE TEST

The acid value of an oil sample is defined as the amount of potassium hydroxide (KOH), in milligrams, required to neutralize the free fatty acids present in one gram of fat.

This test is essential for assessing oil freshness, ensuring quality control, monitoring process efficiency, detecting adulteration, and predicting shelf life.

The acid value of the oil is determined using the following formula:

$$\text{AV (mgKOH/gram)} = \frac{\mathbf{56.1 \times V \times N}}{\mathbf{W}}$$

Where;

AV = Acid Value

56.1 = Molar mass of KOH (g/mol)

V = Volume of KOH solution used for titration (mL)

N = Normality of the KOH solution (mol/L)

W = Weight of the oil or fat sample (g)

PROCEDURES

1. 0.05M solution of KOH was prepared by dissolving 2.8grams (mass of KOH corresponding to 0.05M KOH) of KOH pellets in distilled water and topped to a volume of 1 liter.
2. Using a weighing balance, 1 gram of oil sample was weighed into a beaker.
3. 10ml of benzene and 10ml of ethanol was added to the oil sample
4. Three drops of phenolphthalein were added to the mixture and titrated against 0.05M solution of KOH until a pink coloration is formed.
5. The reading from the burette was recorded.
6. The test was carried out in triplicates for each of the three oils for better accuracy.

3.3.2.2. SAPONIFICATION VALUE TEST

Saponification value refers to the number of milligrams of potassium hydroxide required t saponify one gram of fat under specified conditions.

Saponification value is used in accessing oil quality, optimizing processes and comparing oils for specific purposes.

The saponification value is calculated with the formular below:

Saponification value (mgKOH) = $\frac{(B-V)\times 56.1 \times M}{W}$

Where:

M = Molarity of standard HCl

B = Titration of blank in milliliter

V = Titration of test sample in milliliter

W = Mass of oil

PROCEDURES

1. 0.5M solution of HCL was prepared.
2. Distilled water was added to 41.6ml the HCl in a 1000ml mark of the standard flask
3. The 0.5M solution of alcoholic KOH was prepared by dissolving KOH in ethanol.
4. 1 gram of oil sample was weighed into a round bottom flask.
5. 50ml of 0.5 alcoholic KOH was added to the oil sample and placed on the heating mantle for reflux

6. Reflux was carried out for 60 minutes at a temperature of 70ºC.
7. The mixture was cooled to room temperature after the reflux.
8. After cooling, the mixture was transferred to conical flask, three drops of phenolphthalein added forming a pink coloration and titrated against o.5M solution of HCl until the oil changes back into its original color.
9. The reading of the burette was recorded.
10. The test was carried out in triplicates for each of the three oils and oil blend for better accuracy.

3.3.2.3. DENSITY VALUE TEST

The density of oil is the mass of oil per unit volume of the oil. Density testing provides valuable insights into the quality, composition and behavior of the oil for optimum use in manufacturing processes.

Density ($\mathcal{P}$) = $\frac{oil\ weight}{oil\ volume}$

PROCEDURES

1. A weighing balance was used to weigh an empty beaker and the value recorded as *beaker weight.*
2. The oil was introduced into same beaker and weighed again; the value recorded as *beaker + oil weight*
3. The two masses were subtracted to get the mass of the oil and the value recorded as *oil weight*
4. The oil was turned into a measuring cylinder and volume recorded as oil volume

5. The density of oil was calculated by dividing the mass of the oil by the corresponding volume of oil.

3.3.2.4. VISCOSITY VALUE TEST

The viscosity of oil is a measure of its resistance to flow under an applied force. Viscosity testing provides valuable insights into the oil's fluidity, molecular composition, and performance under varying temperature conditions. It plays a crucial role in determining the efficiency of oil in lubrication, fuel atomization, and overall suitability for industrial and manufacturing applications.

PROCEDURE

1. A measured volume of the oil sample was poured into the viscometer cup.
2. I ensured the oil reaches the lower bulb of the viscometer without air bubbles.
3. The viscometer was placed in a water bath set to a controlled temperature of 40°C
4. The oil was allowed to reach thermal equilibrium for about 10–15 minutes.
5. The torque reading displayed on the viscometer was then recorded.

3.4 REACTION CHEMISTRY AND MECHANISM

The transesterification reaction converts triglycerides present in the non-edible oils into methyl esters (biodiesel) and glycerol in the presence of methanol and a catalyst. The general reaction mechanism follows:

Triglyceride + 3MeOH → 3Fatty Acid Methyl Ester + Glycerol

3.5 ASPEN PLUS SIMULATION SETUP

Aspen Plus V11 was used to model the transesterification process. The simulation workflow involved the following steps:

3.5.1 PROCESS FLOW DIAGRAM (PFD) DEVELOPMENT

1. The reaction was modeled using an RSTOIC reactor block to represent the transesterification kinetics.
2. Separator blocks were used to separate the biodiesel phase from glycerol and unreacted methanol.
3. The NRTL (Non-Random Two-Liquid) model was used to account for the non-ideal behavior of the reaction mixture.

3.5.2. ECONOMIC ANALYSIS FRAMEWORK

The economic assessment was conducted within Aspen Plus using the economic analyzer tool. The following cost parameters were considered:

1. Capital Costs: Equipment costs (reactor, separators, distillation units).
2. Operating Costs: Raw material costs (oils, methanol, catalyst), energy consumption, and labor.
3. Revenue Estimation: Based on the market price of biodiesel and glycerol.
4. Profitability Metrics: Payback period (PBP), net present value (NPV), and return on investment (ROI).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 OIL CHARACTERIZATION

4.1.1 ACID VALUE TEST FOR NEEM OIL

The following results were obtained at the end of the experiment

Table 4. 1: Titer values for acid value test of Neem Oil

	1^{st}	2^{nd}	3^{rd}
Initial Burette Reading	0.00	0.00	0.00
Final Burette Reading	20.8	21.0	20.5
Volume Required	20.8	21.0	20.5

Average titre value = $\frac{20.8+21.0+20.5}{3}$ = 20.77 ml

Acid value = $\frac{56.1 \text{ x } 0.05 \text{ x } 20.77}{1}$ = 58.25 mg.KOH/g

Table 4.1 above gives the titre values obtained from titration of neem oil sample against 0.05M KOH from which the acid value of the neem oil was calculated and obtained as 58.25 mg KOH/g which is significantly higher than values reported in previous literature.

For instance, Taiwo et al. (2020) reported an acid value of 20.90 mg KOH/g for neem oil. Additionally, a study by Anindita and Souti. (2017) reported an acid value of 34 mg KOH/g for crude neem oil. The considerable variation in acid values across different studies can be

attributed to factors such as the geographical source of the neem seeds, extraction and processing methods, and storage conditions of the oil.

According to the ASTM D6751 standard, the acceptable acid value for biodiesel feedstock is a maximum of 0.5 mg KOH/g.

The neem oil sample in this study exceeds this limit by a substantial margin, indicating a high FFA content. High FFA levels can lead to soap formation during the transesterification process, resulting in lower biodiesel yields and difficulties in product separation.

To address this issue, a pretreatment step, such as acid esterification, is necessary to reduce the FFA content before proceeding with the base-catalyzed transesterification. This approach has been demonstrated to be effective in a previous studies Aransiola et al. (2011). Implementing such a pretreatment will help in achieving a more efficient conversion of neem oil into biodiesel, ensuring compliance with biodiesel quality standards.

In conclusion, the elevated acid value observed in this neem oil sample underscores the importance of pretreatment processes to reduce FFA levels, thereby enhancing its suitability for biodiesel production.

4.1.2 ACID VALUE TEST FOR CASTOR OIL

The following results were obtained at the end of the experiment

Table 4. 2: Titer values for acid value test of castor oil

	1^{st}	2^{nd}	3^{rd}
Initial Burette Reading	0.00	0.00	0.00
Final Burette Reading	18.0	19.0	18.6
Volume Required	18.0	19.0	18.6

Average titre value = $\frac{18.0 + 19.0 + 18.6}{3}$ = 18.53 ml

Acid value = $\frac{56.1 \text{ x } 0.05 \text{ x } 18.53}{1}$ = 52.0 mg.KOH/g

Table 4.2 provides the titre values resulting from the titration of castor oil sample with 0.05M KOH, yielding an acid value of 52.0mg KOH/g. A comparison with literature show that result obtained is significantly higher than those of Ofori et al.(2023), who achieved value of 0.5 mgKOH/g respectively. The significant disparity between the acid value obtained in this study and those reported in the literature may be attributed to several factors, including differences in the geographical source of the castor seeds, variations in extraction and processing methods, and storage conditions of the oil.

The standard acid value for castor oil suitability in biodiesel production, as per ASTM763, ranges from 0.4 to 4.0 mgKOH/g. The obtained acid value exceeds this standard, suggesting high levels of free fatty acid. Elevated FFA levels can lead to soap formation during the transesterification process, resulting in lower biodiesel yields and complications in product separation. Consequently, the oil requires pretreatment via esterification to reduce the acid value to ASTM763's acceptable range.

4.1.3 ACID VALUE TEST FOR WASTE COOKING VEGETABLE OIL

The following results were obtained at the end of the experiment

Table 4. 3: Titer values for acid value test of waste cooking vegetable oil

	1^{st}	2^{nd}	3^{rd}
Initial Burette Reading	0.00	0.00	0.00
Final Burette Reading	2.00	3.00	2.50
Volume Required	2.00	3.00	2.50

Average titre value = $\frac{2.0 + 3.0 + 2.5}{3}$ = 2.5 ml

Acid value = $\frac{56.1 \text{ x } 0.05 \text{ x } 2.5}{1}$ = 7.01 mgKOH/g

In Table 4.3 above, the titre values resulting from titrating waste cooking oil sample with 0.05M KOH are provided, leading to an acid value of 7.01 mgKOH/g. which is notably higher than values reported in existing literature.

For instance, Ali et al. (2016) reported an acid value of 2.04 mg KOH/g for waste cooking oil (WCO), while Ramadhas et al. (2024) found a value of 3.04 mg NaOH/g, which was reduced to 0.98 mg NaOH/g after optimized esterification. Additionally, a study by Patel et al. (2019) highlighted that the acid value of WCO varies based on the degree of usage and the type of food items originally fried in the oil. The significant disparity between the acid value obtained in this study and those reported in the literature may be attributed to several factors, including differences in the source of the waste oil, variations in cooking practices, the number of frying cycles, and storage conditions of the oil.

According to the ASTM D6751 standard, the acceptable acid value for biodiesel feedstock is a maximum of 0.5 mg KOH/g. The WVO sample in this study exceeds this limit substantially, indicating a high FFA content. Elevated FFA levels can lead to soap formation during the transesterification process, resulting in lower biodiesel yields and complications in product separation.

To mitigate this issue, a pretreatment step, such as acid esterification, is necessary to reduce the FFA content before proceeding with base-catalyzed transesterification. This approach has been demonstrated to be effective in previous studies. Implementing such a pretreatment will facilitate a more efficient conversion of WVO into biodiesel, ensuring compliance with established quality standards.

4.1.4 ACID VALUE TEST FOR THE OIL BLEND (NEEM, CASTOR AND WVO)

The following results were obtained at the end of the experiment

Table 4. 4: Titer values for acid value test of the oil blend

	1^{st}	2^{nd}	3^{rd}
Initial Burette Reading	0.00	0.00	0.00
Final Burette Reading	7.80	8.00	7.60
Volume Required	7.80	8.00	7.60

Average titre value = $\frac{7.8 + 8 + 7.6}{3}$ = 7.80 ml

Acid value = $\frac{56.1 \text{ x } 0.05 \text{ x } 7.8}{1}$ = 21.90 mgKOH/g

In Table 4.4 above, the titre values resulting from titrating the oil blend sample with 0.05M KOH are provided, leading to an acid value of 21.90 mgKOH/g. The acid value of an oil blend is a key indicator of its free fatty acid (FFA) content, which directly impacts its suitability for biodiesel production. In this study, the oil blend sample exhibited an acid value of 21.90 mg KOH/g, which is significantly high compared to the standard requirements for biodiesel feedstock.

A comparison with literature reveals that the acid values of individual oils in the blend can influence the final result. Neem oil, castor oil, and waste cooking oil have been reported to exhibit varying acid values depending on factors such as oil source, extraction method, and storage conditions. For instance, Ali et al. (2016) reported an acid value of 31.86 mg KOH/g for neem oil, while Ramadhas et al. (2024) found an acid value of 33.29 mg KOH/g for castor oil. Patel et al. (2019) determined the acid value of waste cooking oil to be 6.49 mg KOH/g. The high acid value obtained in this study suggests that at least one of the oils in the blend contains a considerable amount of free fatty acids (FFA), contributing to the overall increase in acidity.

According to ASTM D6751 and EN 14214, the maximum allowable acid value for biodiesel feedstock is 0.5 mg KOH/g to minimize soap formation and catalyst deactivation during transesterification (Knothe et al., 2005). The acid value obtained in this study far exceeds this limit, indicating that pretreatment is necessary before the oil blend can be effectively converted into biodiesel.

4.1.5 SAPONIFICATION VALUE TEST FOR NEEM OIL

The following results were obtained at the end of the experiment

Table 4. 5: Titer values for saponification test of neem oil

	1^{st}	2^{nd}	3^{rd}
Initial Burette Reading	0.00	0.00	0.00
Final Burette Reading	46.1	46.2	46.0
Volume Required	46.1	46.2	46.0

Average titre value = $\frac{46.1+ 46.2 + 46.0}{3}$ = 46.1 ml

Saponification value = $\frac{(52.9 - 46.1) \text{ x } 56.1 \text{ x } 0.5}{1}$ = 190.74 mgKOH

In Table 4.5 above, the titre values resulting from the saponification value test of neem oil sample are provided leading to a saponification value of 190.74mgKOH/g.

Upon comparison, it is observed that the saponification value obtained is slightly close to that reported by Kale et al. (2020) and Yami et al. (2020), who carried out the same experiment and got saponification values of 198.11 mg KOH/g and 196.30 mg KOH/g, respectively. Variation in results obtained compared to literature may be due to oil sample source, oil extraction and processing methods, analytical errors in the titration test, or storage conditions of the neem oil.

According to ASTM763, the standard saponification value for neem oil suitable for biodiesel production ranges from 200 to 220 mgKOH/g. However, the obtained saponification value lower than this standard, indicating elevated levels of free fatty acid. Thus, pretreatment via esterification is necessary to reduce the acid value to the acceptable range defined by ASTM763.

4.1.6 SAPONIFICATION VALUE TEST FOR CASTOR OIL

The following results were obtained at the end of the experiment

Table 4. 6: Titer values for saponification test of castor oil

	1^{st}	2^{nd}	3^{rd}
Initial Burette Reading	0.00	0.00	0.00
Final Burette Reading	47.0	46.5	46.3
Volume Required	47.0	46.5	46.3

Average titre value = $\frac{47 + 46.5 + 46.3}{3}$ = 46.6 ml

Saponification value = $\frac{(52.9 - 46.6) \text{ x } 56.1 \text{ x } 0.5}{1}$ = 176.71 mgKOH

In Table 4.6 above, the titre values resulting from the saponification value test of castor oil sample are provided leading to a saponification value of 180.92mgKOH. which is within the range of values reported in literature. Mandal (2023) and Ofori et al. (2023) obtained 177.43 mg KOH/g and 190 mg KOH/g, respectively. The variation observed between this study and existing literature may be attributed to differences in oil source, extraction methods, processing conditions, storage duration, and potential analytical errors during the experiment.

According to ASTM D6751 and EN 14214, the recommended saponification value for biodiesel production ranges between 200 and 220 mg KOH/g (Knothe, 2010). The value obtained in this study is lower than the standard, suggesting that the oil contains a significant proportion of long-chain fatty acids. This characteristic can affect fuel properties such as viscosity and volatility, making the oil less ideal for biodiesel conversion without modification.

To improve its suitability for biodiesel production, the oil requires pretreatment through acid esterification or alkaline refining to optimize its properties before undergoing transesterification

(Canakci & Gerpen, 1999). Esterification helps to reduce free fatty acid (FFA) content, while refining can remove impurities that may hinder biodiesel yield.

4.1.7 SAPONIFICATION VALUE TEST FOR WASTE VEGETABLE OIL

The following results were obtained at the end of the experiment

Table 4. 7: Titer values for saponification test of waste cooking vegetable oil

	1^{st}	2^{nd}	3^{rd}
Initial Burette Reading	0.00	0.00	0.00
Final Burette Reading	46.0	46.4	45.5
Volume Required	46.0	46.4	45.5

Average titre value = $\frac{46.0 + 46.4 + 45.5}{3}$ = 46.0 ml

Saponification value = $\frac{(52.9 - 46)\ \text{x}\ 56.1\ \text{x}\ 0.5}{1}$ = 193.54 mgKOH/g

In Table 4.7 above, the titre values resulting from the saponification value test of waste cooking oil sample are provided leading to a saponification value of 193.54mgKOH/g

Upon comparison, it is observed that the saponification value obtained is significantly close to those reported by Yusof et al. (2021) and Haq et al. (2021) who carried out the same experiment and got a saponification value of 207.40 mg KOH/g, 187.83 mg KOH/g respectively. Variations in results obtained to literature may be due to oil sample source, oil extraction and processing method, analytical errors in carry test or storage conditions of the waste cooking oil.

According to ASTM763, the standard saponification value for oil suitable for biodiesel production ranges from 200 to 220 mgKOH/g. However, the obtained saponification value higher than this standard, indicating elevated levels of free fatty acid. Thus, pretreatment via esterification is necessary to reduce the acid value to the acceptable range defined by ASTM763 to ensure suitability for biodiesel production

4.1.8 SAPONIFICATION VALUE TEST FOR THE OIL BLEND

The following results were obtained at the end of the experiment

Table 4. 8: Titer values for saponification test of the Oil Blend

	1^{st}	2^{nd}	3^{rd}
Initial Burette Reading	0.00	0.00	0.00
Final Burette Reading	45.75	45.8	46.0
Volume Required	45.75	45.8	46.0

Average titre value = $\frac{45.75 + 45.8 + 46.0}{3}$ = 45.85 ml

Saponification value = $\frac{(52.9 - 45.85)\ \text{x}\ 56.1\ \text{x}\ 0.5}{1}$ = 197.75 mgKOH/g

In Table 4.8 above, the titre values resulting from the saponification value test of the oil blend sample are provided leading to a saponification value of 197.75mgKOH/g. This value represents the amount of potassium hydroxide (KOH) required to completely saponify one gram of the oil blend, indicating the presence of short- and medium-chain fatty acids in the sample.

Upon comparison with existing literature, the obtained saponification value is slightly close to those reported by Ivanova et al. (2022) and Wazed et al. (2021), who recorded values of 196.89 mgKOH/g and 196.30 mgKOH/g, respectively. However, it is slightly lower than the values reported by Singh et al. (2023), who obtained a saponification value of 205.45 mgKOH/g for a similar oil blend. Differences in values may be attributed to factors such as: Variations in oil composition (due to the blending ratio of neem, castor, and waste cooking oil). Differences in oil extraction and processing methods. Storage conditions that may lead to oxidation or hydrolysis of fatty acids. Analytical errors during titration or experimental setup.

According to ASTM D5558 and EN 14104 standards for biodiesel production, an ideal saponification value typically ranges from 200 to 220 mgKOH/g for optimal fuel properties. The obtained saponification value of 197.75 mgKOH/g is slightly below this standard, indicating a relatively higher proportion of long-chain fatty acids in the oil blend. This suggests that while the oil blend may still be suitable for biodiesel production, additional pretreatment steps such as acid esterification or alkaline refining may be necessary to optimize its fuel properties and improve biodiesel yield.

4.1.9 BLANK TITRE VALUES

The following results were obtained at the end of the experiment

Table 4. 9: Titer values for blank

	1^{st}	2^{nd}	3^{rd}
Initial Burette Reading	0.00	0.00	0.00

Final Burette Reading	53.0	53.2	52.6
Volume Required	53.0	53.2	52.6

Average titer value = $\frac{53 + 53.2 + 52.6}{3}$ = 52.9 ml

4.1.10. DENSITY VALUE TEST FOR THE OIL

The following results were obtained at the end of the experiment

Table 4. 10: Density Values obtained

Oil Type	Volume(ml)	Mass(g)	Density(g/ml)
Neem Oil	100	92.32	0.9232
Castor Oil	100	97.218	0.9722
Waste Cooking Vegetable Oil	100	95.378	0.9538
Oil Blend	50	47.820	0.9560

The results presented in Table 4.9 indicate the densities of neem oil, castor oil, waste vegetable oil (WVO) and oil blend at room temperature. According to the study conducted by researchers Das et al.(2021), Mandal (2023) and Haq et al. (2021) the density values obtained were 0.91 g/ml for neem oil, 0.962 g/ml for castor oil, and 0.9077 g/ml for waste vegetable oil .Upon comparing these obtained values with those reported in the literature, it becomes apparent that they closely align with the values found in previous research. This consistency between the obtained data and the literature provides validation and reliability to the experimental findings.

According to ASTM standards for oil density, oils falling within the density range of 0.8 to 0.9 g/ml are considered to be within the acceptable range for biodiesel production. Results obtained neem oil, castor oil and waste cooking oil falls within this range thus is suitable for biodiesel production.

4.1.11 VISCOSITY VALUE TEST FOR THE OIL

The following results were obtained at the end of the experiment

Table 4. 11: Viscosity Values obtained

Oil Type	Temperature (Degree Celsius)	Viscosity (mPa.s)
Neem Oil	40	14.9
Castor Oil	40	32.5
Waste Cooking Vegetable Oil	40	6.78
Oil Blend	40	12.8

4.2 BIODIESEL SIMULATION

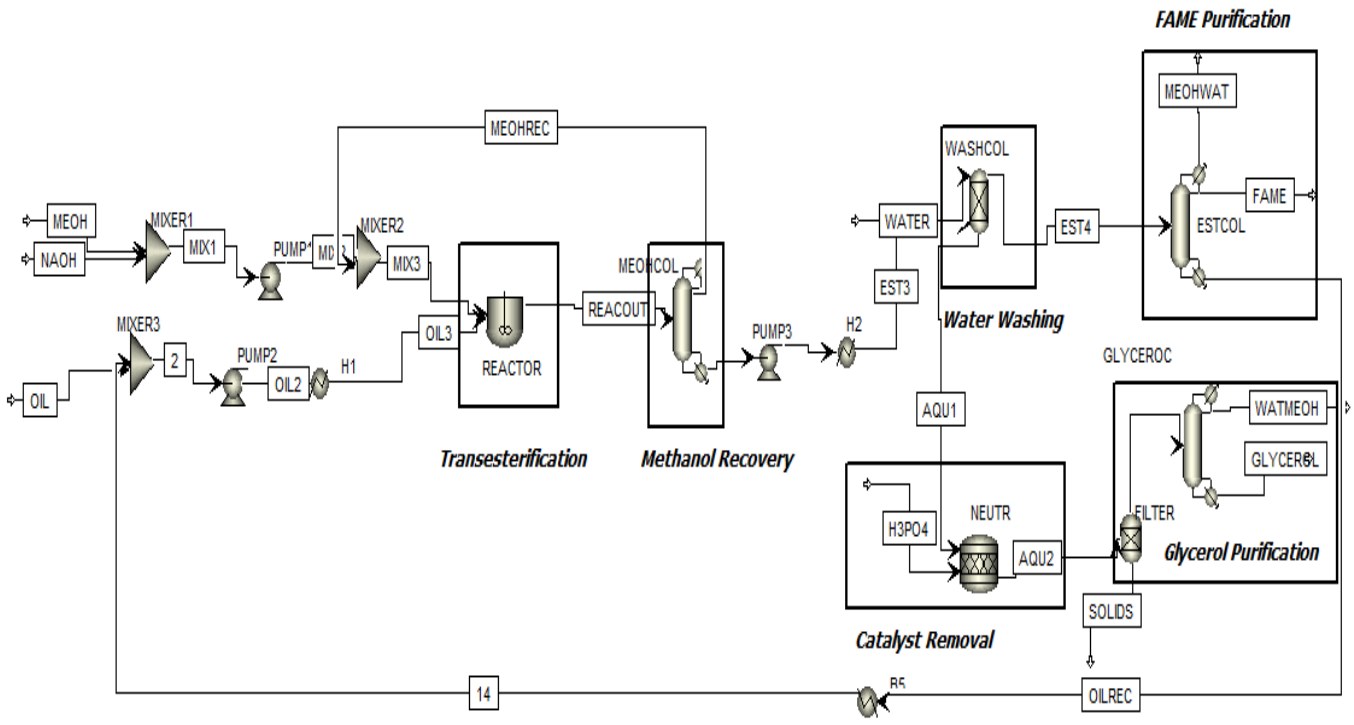

Figure 4. 1 Biodiesel Flowsheet

$$\textbf{Biodiesel Yield (\%)} = \left(\frac{\text{Mass Flowrate of Biodiesel } \left(\frac{\text{kg}}{\text{hr}}\right)}{\text{Mass Flowrate of Oil Feedstock } \left(\frac{\text{kg}}{\text{hr}}\right)} \right) \times 100$$

Biodiesel Mass Flowrate = 1004.79 kg/hr

Oil Feedstock Mass Flowrate = 1100 kg/hr

$$\text{Biodiesel Yield (\%)} = \left(\frac{1004.79 \left(\frac{\text{kg}}{\text{hr}}\right)}{1100 \left(\frac{\text{kg}}{\text{hr}}\right)} \right) \times 100$$

$$= 91.3\%$$

4.2.1 ECONOMIC ANALYSIS DATA

The economic assessment was conducted within Aspen Plus using the economic analyzer tool.

Table 4. 12: Overall economic data of biodiesel production plant

Total Capital Investment	$7,020,220	₦10,603,000,000
Total Installed Equipment Cost	$2,721,600	₦4,111,000,000
Total Operating Cost	$1,793,070 per year	₦2,710,000,000 per year
Total Utilities Cost	$128,445 per year	₦194,000,000 per year
Total Revenue from Biodiesel Production	$15,678,800 per year	₦23,678,000,000 per year
Batch Size	12,635.23 kg MP	12,635.23 kg MP
Cost Basis Annual Rate	16,678,501 kg MP per year	16,678,501 kg MP per year
Unit Production Price	$0.94/kg MP	₦1,420.00/kg MP
Unit Production Income	$1.23/kg MP	₦1,860.00/kg MP
Margin of Profit	88.56%	88.56%
Investment Return	197.78%	197.78%
Reimbursement Time	0.51 years (6 months)	0.51 years (6 months)
Internal Rate of Return (IRR) After Tax	28.2%	28.2%
Net Present Value (NPV) at 10% Interest Rate	$78,295,380	₦118,180,000,000

The economic analysis of the proposed biodiesel production process was carried out using Aspen Process Economic Analyzer, and the results are summarized in Table 4.12.

The economic analysis of the proposed biodiesel production process in this study was compared with findings from a previous study by Sangeetha et al. (2023). Both analyses present similar total capital investment values, with this study estimating ₦10,603,000,000, while the referenced study reports $13,124,000 (approximately ₦10.6 billion, assuming an exchange rate of ₦810/$) (Sangeetha et al., 2023). However, notable differences exist in operating costs and revenue projections. In this study, the annual operating cost was calculated to be ₦2,710,000,000, whereas the referenced study reports a significantly higher operating cost of $15,641,000 (₦12.7 billion). Additionally, the estimated utilities cost in this study is ₦194,000,000, while the referenced study reports a much lower value of $11,411 (₦9.2 million) (Sangeetha et al., 2023).

Revenue projections also exhibit variations, with this study estimating an annual revenue of ₦23,678,000,000 compared to $20,455,000 (₦16.6 billion) in the referenced study. This disparity is reflected in profitability metrics, as the margin of profit in this study is calculated to be 88.56%, significantly higher than the 23.54% reported in the referenced study (Sangeetha et al., 2023). Similarly, the return on investment (ROI) in this study is estimated at 197.78%, compared to 35.72% in the referenced study. Furthermore, this study predicts a remarkably short payback period of 0.51 years (6 months), whereas the referenced study estimates a payback period of 2.8 years. Despite these differences, both studies report an identical internal rate of return (IRR) of 28.2%. However, the net present value (NPV) calculations show a stark contrast, with this study estimating ₦118,180,000,000, whereas the referenced study reports $19,287,000 (₦15.6 billion) (Sangeetha et al., 2023).

Overall, this study suggests a more financially viable biodiesel production process, with higher revenue, a faster payback period, and a greater return on investment. In contrast, the referenced study presents a more conservative assessment, characterized by higher operating costs and a lower

profit margin. These findings reinforce the economic attractiveness of the proposed process, demonstrating its potential for profitability and sustainability.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

This study focused on the technoeconomic analysis of the transesterification reaction of a ternary blend of non-edible oils, with simulations performed in Aspen Plus. The research aimed to evaluate the feasibility of biodiesel production from neem oil, castor oil, and waste cooking oil, considering both process efficiency and economic viability. The simulation results demonstrated that the reaction proceeded efficiently in the presence of a composite heterogeneous catalyst, which played a crucial role in enhancing reaction rates while minimizing soap formation. The use of heterogeneous catalysts offers advantages such as reusability, minimal side reactions, and lower energy consumption compared to conventional homogeneous catalysts.

The yield of biodiesel was significantly influenced by reaction temperature, catalyst loading, and methanol-to-oil molar ratio. Through Aspen Plus simulations, the optimal conditions for maximizing biodiesel production were identified. The results indicated that higher methanol-to-oil ratios improved conversion but required optimization to balance cost-effectiveness. The need for pretreatment, especially for oils with high free fatty acid (FFA) content, was evident as it helped reduce the acid value and improve overall biodiesel yield.

A detailed technoeconomic analysis of the biodiesel production process was conducted. The capital investment, operating costs, and revenue streams were analyzed to determine key economic indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), margin of profit, and payback period. The results showed that the process is economically viable, with a positive investment return and a reasonable payback period. However, further cost reductions—particularly

in catalyst production and methanol consumption—could improve profitability and long-term sustainability. Additionally, biodiesel from this process has a lower carbon footprint compared to fossil fuels, making it a more environmentally friendly energy source. The utilization of waste cooking oil further enhances sustainability by promoting waste-to-energy conversion and reducing environmental pollution.

5.2 RECOMMENDATIONS

It is recommended that neem oil undergo pretreatment via esterification to reduce its acid value (AV) to acceptable levels. For castor oil, further investigation into effective pretreatment methods is necessary to enhance its suitability for biodiesel production. Similarly, waste cooking oil should undergo esterification to lower its AV and ensure compliance with biodiesel production standards. While each oil exhibits some deviations from ASTM standards in specific parameters, they still hold significant potential for biodiesel production. Implementing appropriate pretreatment techniques can address these deviations, highlighting the need for further research and experimentation to optimize their utilization.

The heterogeneous catalyst used in the simulation should be optimized for better reusability and longer lifespan to reduce operating costs. Further research should also explore alternative low-cost composite catalysts with higher activity and stability in transesterification reactions. Cost analysis should be expanded in Aspen Plus to determine the break-even point and economic viability under different production scales. The potential for co-product utilization (e.g., using glycerol as an industrial feedstock) should be further explored to maximize revenue streams.

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APPENDIX

AV (mgKOH/gram) = $\frac{\mathbf{56.1 \times V \times N}}{W}$

Where;

AV = Acid Value

56.1 = Molar mass of KOH (g/mol)

V = Volume of KOH solution used for titration (mL)

N = Normality of the KOH solution (mol/L)

W = Weight of the oil or fat sample (g)

Saponification value (mgKOH) = $\frac{(B-V) \times 56.1 \times M}{W}$

Where:

M = Molarity of standard HCl

B = Titration of blank in milliliter

V = Titration of test sample in milliliter

W = Mass of oil

Density ($\mathcal{f}$) = $\frac{oil\ weight}{oil\ volume}$