Experimental Investigation of Biodiesel Produced from Various Feedstocks: Life Cycle Assessment Approach

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AUTHOR'S DECLARATION

I, Muhammad Aqil Khan, Reg. No 114-FET/MSME/F23, student of MS in Mechanical engineering, from session 2023, certify that the research work titled "**Experimental Investigation of Biodiesel Produced from Various Feedstocks: Life Cycle Assessment Approach**" is wholly my own work. This research work has not been presented anywhere else for assessment. Wherever the material is used from other sources it is properly referred to and acknowledged.

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DEDICATION

I would like to dedicate this work to my family, especially my parents. Their continuous support and motivation for the timely submission of the thesis and for this accomplishment.

Sincerely

Muhammad Aqil Khan

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I am thankful to Almighty ALLAH Subhana-Wa-Tala for his Great guidance towards me throughout this research work at every single step of this research work. Afterwards, whoever helped me throughout the course of this thesis, either my family or any individual; I would be nothing without this help.

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Muhammad Aqil Khan

ABSTRACT

Biodiesel plays a key role in achieving net-zero emissions due to its significantly lower greenhouse gas emissions and its contribution to waste reduction. This study presents an experimental investigation into the chemical properties, environmental impacts, and social considerations of biodiesel produced from various waste sources. Transesterification was used to convert these waste oils to biodiesel with conversion efficiency dependent on the acid value of the type of feedstock. The highest yield, achieving 85% conversion efficiency, was recorded for a sample with an acid value of 3.5 mgKOH/g. Fourier Transform Infrared Spectroscopy (FTIR) and Gas Chromatography-Mass Spectrometry (GC-MS) were used to determine the chemical composition of biodiesel Produced. The FTIR analysis confirmed successful transesterification, with peak variations at 1198 cm^{-1} and 1377 cm^{-1} indicating methyl ester formation and triglyceride conversion, respectively. Heating value analysis showed that serena-based biodiesel exhibited the highest heating value, while fuel blends containing more than 50% biodiesel maintained a constant heating value. Additionally, biodiesel's higher flash point compared to fossil diesel enhances its safety for storage and transportation. The study also integrated machine learning models to optimize production parameters, predict emissions, and improve process efficiency. The environmental life cycle assessment (LCA) was conducted using SimaPro V9.5.0.2, revealing that biodiesel derived from waste cooking oil exhibited the lowest carbon footprint compared to palm oil and chicken feather oil. Biodiesels from different feedstocks reduced carbon emissions by 70%, 64%, 63%, and 65%, respectively, compared to fossil diesel. Social analysis was conducted which reveals strong correlations between familiarity, knowledge, and willingness to adopt biodiesel, highlighting the need for targeted educational initiatives. Bridging the gap between awareness and knowledge through strategic communication and policy support can significantly enhance biodiesel adoption across sectors.

This study underscores the practical adaptation of biodiesel production from waste resources, offering environmental benefits, economic viability, and enhanced energy security. Policy recommendations include regulatory frameworks for biodiesel integration, waste-to-energy initiatives, and leveraging machine learning for process optimization. The findings provide valuable insights for policymakers, industry

stakeholders, and researchers striving to promote biodiesel adoption as a sustainable alternative to conventional diesel.

Keywords: Waste to biodiesel, transesterification process, chemical properties, experimental investigation, SimaPro, machine learning, life cycle assessment.

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ABBREVIATIONS

ANN – Artificial Neural Network

AV – Acid Value

Bx – x% Biodiesel (100-x)% fossil diesel

CV – Calorific Value

FFA – Free Fatty Acids

FP – Flash Point

FTIR – Fourier Transform Infrared Spectroscopy

GCMS – Gas Chromatography and Mass Spectroscopy

GHG – Greenhouse Gases Emissions

GWP – Global Warming Potential

HV – Heating Value

LCA – Life Cycle Assessment

ML – Machine Learning

SG – Specific Gravity

SLCA – Social Life Cycle Assessment

ELCA – Environmental Life Cycle Assessment

SYMBOLS

W	Weight of Feedstock
T	Transportation cost
P	Processing cost
Q	Quantity of feedstock
E	Emissions
i	Day
j	Type of feedstock

Chapter 1 Introduction

For decades, diesel derived from fossil fuels has been widely used, leading to the diminution of natural resources and contributing to environmental degradation, a major driver of climate change. The demand for energy has surged worldwide, especially after the industrial revolution and with rising living standards and population growth in the early 20th century. Reports indicate that global energy consumption is estimated to increase by 53%, with demand projected to grow from 13,972 million tonnes of oil equivalent (Mtoe) in 2019 to 16,395 Mtoe by 2040. Fossil based fuels including oil, coal, and natural gas have dominated the global energy mix, making up about 84% of total consumption in 2019. However, their continued use raises concerns about resource depletion, environmental pollution, and greenhouse gas emissions that accelerate climate change.

Global greenhouse gas (GHG) emissions reached a record high of 57.1 $GtCO_2e$ in 2023, marking a 1.3% increase from 2022. This growth rate exceeds the average annual increase of 0.8% recorded between 2010 and 2019, the decade before the COVID-19 pandemic. The rise in emissions was observed across all sectors and sources, except for land use, land-use change, and forestry (LULUCF) CO_2. The power generating sector remained the largest contributor, emitting 15.1 $GtCO_2e$, followed by transportation sector at 8.4 $GtCO_2e$, agriculture at 6.5 $GtCO_2e$, and industry at 6.5 $GtCO_2e$ as shown in Figure 1.1. International aviation, which saw a significant decline during the pandemic, experienced the highest increase at 19.5% compared to 2022, signaling a return to pre-pandemic levels. Other rapidly growing sources in 2023, with increases exceeding 2.5%, included emissions from fuel production (such as oil and gas infrastructure and coal mines), road transport, and energy sector industrial emissions[1].

The transportation industry alone is accountable for nearly 23% of global energy-related CO_2 emissions[2], [3]. The transportation sector primarily relies on fossil fuels, contributing 3-4% of the total emissions approximately of the total emissions making it the second-largest consumer of fossil-based energy after industry. Road transport contributes significantly to urban pollution, accounting for 20-30% of emissions in cities. To mitigate these emissions, various strategies and technologies are being explored, focusing on decarbonization and the adoption of cleaner energy sources[4].

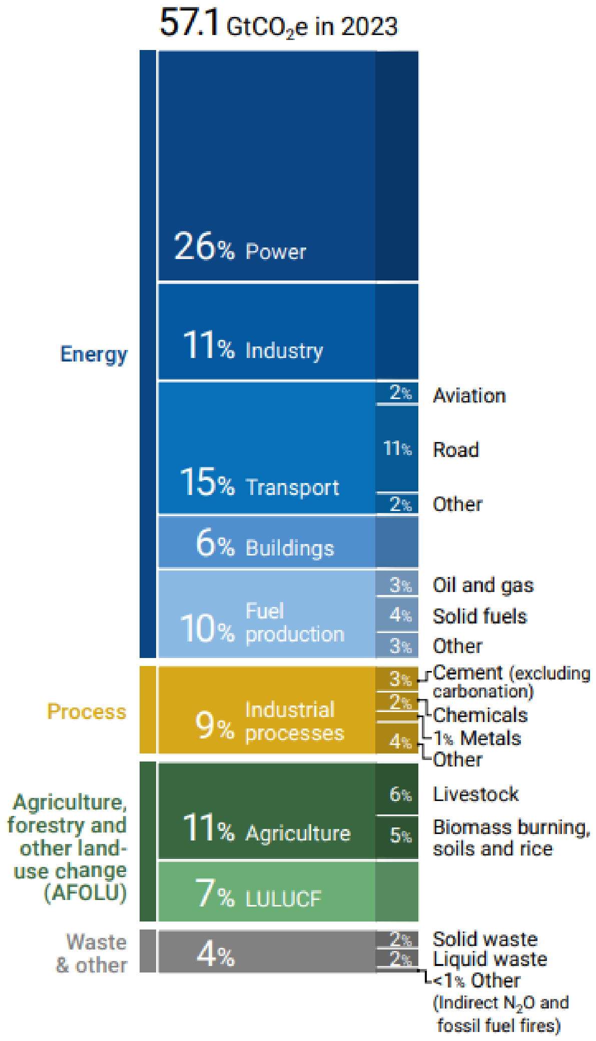


Figure 1.1 GHG Emissions by sector in 2023[1]

Integrating renewable energy into the energy sector is essential for achieving carbon neutrality, lowering carbon footprint, and reducing reliance on fossils. The rapid depletion of typical energy resources and their environmental impact are major concerns for both developed and developing nations. Additionally, many of these traditional energy resources are located in politically uneven regions, leading to uncertainties in supply and fluctuations in global oil prices[5].

The transition from fossil fuels to alternative fuels is driven by environmental concerns, energy security, and the need for sustainable development. Various alternative fuels have emerged, including biomass, hydrogen, and biofuels, which offer potential benefits in reducing emissions and reliance on fossil resources. Biomass can be converted into biofuels like ethanol and biodiesel, which are renewable and can significantly reduce greenhouse gas emissions[6]. Hydrogen considered a clean fuel, which can be produced from different sustainable sources and has the potential to provide alternative to fossil based fuels in many applications[7]. Fuels like syngas, produced from biomass or waste materials, can be utilized in internal combustion engines, providing a renewable alternative to traditional fuels[8].

Biofuels, particularly biobased i-e biodiesel, have gained recognition as viable alternatives to fossil fuels. Biodiesel is a renewable, bio based fuel produced from organic feedstocks such as vegetable oils (VO), animal fats, and waste frying oils (WFO). Its adoption offers numerous advantages, including reduced GHG emissions, decreased reliance on depleting fossil reserves, and enhanced energy security. Various studies have shown that the lifecycle emissions of biodiesel are significantly fewer than those of traditional diesel, with reductions of up to 73% in GHG emissions when biodiesel replaces fossil diesel.

Biodiesel started extensively produced in the early 1990s, and output has continually risen subsequently thereafter. The global biodiesel sector is one of the most rapidly expanding in the chemical industry's history. World capacity, output, and consumption of biodiesel expanded on average by 32% per year between 2000 and 2005, and the industry seems set for even greater growth rates. In the years leading up to 2008 and beyond, capacity will increase by 115% each year, while demand will increase by 101% per year. Germany, the world's largest biodiesel market, has removed taxes on biofuels. The country aims to promote the use of 100% pure biodiesel, which is now available at more than 1,500 public fueling stations[9].

Biodiesel is a renewable liquid fuel made by chemically processing vegetable oils or animal fats with alcohol. It can be use in diesel engines alone or be blended with petroleum diesel. As defined by ASTM International, biodiesel consists of long-chain monoalkyl esters created from fatty acids found in renewable sources, positioning it as a practical substitute for traditional diesel fuel.

Blends of biodiesel with regular diesel are labeled as "BX," where "X" represents the percentage of biodiesel in the mix. For example, "B5" means the fuel contains 5% biodiesel and 95% conventional diesel, while "B100" refers to 100% biodiesel with no petroleum diesel added.

One of the main benefits of biodiesel production is the wide range of feedstocks available, allowing for flexibility in resource use and adaptation to local conditions.

However, different feedstocks have varying characteristics, such as fatty acid configuration, which can affect the characteristic and performance of the biodiesel. For example, soybean oil typically contains around 11% palmitic acid, 4% stearic acid, 23% oleic acid, 54% linoleic acid, and 8% linolenic acid. In contrast, waste cooking oil tends to have a higher concentration of saturated fatty acids due to the frying process[10].

Biodiesel offers several benefits as a replacement to conventional diesel fuel. Some key advantages include:

i. Extracted from renewable sources such as bio based edible/non edible oils.
ii. Lower toxicity compared to traditional diesel.
iii. Reduced emissions of pollutants like carbon monoxide and particulate matter.
iv. Lesser health risks due to decreased release of carcinogenic compounds.
v. No sulfur (SO_2) contents in emissions.
vi. Higher flash point, enhancing safety.
vii. Can be used in blend form with diesel(fossil) in any ratio and during fuel supply.
viii. Provides excellent lubrication properties.
ix. Compatible with conventional diesel engines without requiring modifications.
x. Can utilize waste cooking oils and fat residues as raw materials.

Apart from the advantage there are several disadvantages of using biodiesel. Some of the disadvantages are listed below.

i. Marginally excessive fuel utilization due to its lesser calorific value.
ii. Increased NOx emissions compared to diesel.
iii. Freezing point is slightly higher, which can be problematic in cold climates.
iv. Potential to damage components that are made of plastic and rubber when used in pure form.
v. Lower stability over time.

It must be noted that the advantage of the biodiesel may be reduced when it is used in blended from with the traditional fossil diesel.

1.1 Problem statement

Disposal of animal fats and waste oil pollutes the underground water bodies as well as causing other environmental problems. In addition to that, dependency on fossil-based fuel has caused significant environmental degradation as well as economics challenges. Biodiesel, a renewable and green fuel alternative, provides a viable solution for the reduction of GHG emissions and lessens the resilience on the fossil fuel sources. Transforming the wastes to biodiesel will not only mitigate the pollution but also meets the increasing energy demand. Despite extensive research on biodiesel production, there is still a gap in understanding the experimental investigation, environmental lifecycle impact, and social acceptance of biodiesel derived from diverse waste feedstocks. Existing studies primarily focus on individual aspects, such as fuel characteristics or environmental evaluation, but often lack an integrated approach that combines experimental analysis, life cycle assessment (LCA), and social evaluation. Additionally, applying machine learning to biofuels for optimizing production efficiency and supply chain management remains challenging, particularly due to fluctuations in feedstock availability.

1.2 Research Objectives

The main objectives of this research is to conduct a comprehensive life cycle assessment(LCA) and experimental investigation of biodiesel produced from varied feedstocks. The specific objectives are:

1. To conduct experimental investigations on the physio chemical properties and characterization of biodiesel produced from varied feedstocks, including fuel properties.
2. To perform the environmental Impact Assessment of biodiesel production, such as GHG emissions, and natural resource depletion.
3. To perform complete life cycle assessment of biodiesel production from different feedstocks, including edible oil and animal fats especially from a social perspective.
4. To develop predictive models for estimating biodiesel yield, production costs, and carbon emissions under different feedstock scenarios.

1.3 Significance of Research

This research aims to thoroughly evaluate biodiesel production using various feedstocks, including vegetable oils, fats, and used cooking oils. By integrating life cycle assessment (LCA) with experimental analysis, the study will enhance understanding of the environmental performance and fuel properties of biodiesel derived from diverse sources. The outcomes of this investigation hold significant importance which include:

- Through a comparative analysis of LCA and experimental data, this study will determine the most sustainable, ecofriendly, and economical feedstocks for biodiesel production. The findings will provide valuable guidance to policymakers, researchers, and industry stakeholders in selecting feedstocks that optimize quality, yield, and environmental impact.
- Experimental analysis of biodiesel properties including fuel characteristics such as flash point, heating value, specific gravity and characterization of biodiesel from different feedstock will provide insights for selection and use of feasible and sustainable feedstock for biodiesel production with enhanced properties fostering more sustainable production practices.
- Using waste cooking oils and animal fats as biodiesel feedstock offers the dual benefit of reducing dependence on virgin vegetable oils and diverting waste away from landfills. This research will examine the advantages and challenges of employing these unconventional feedstocks, emphasizing their potential role in advancing a circular economy.
- The environmental LCA will assess the carbon emissions associated with biodiesel production and use, highlighting biodiesel's potential to lower carbon footprints. This research will underline the role of biodiesel in achieving global decarbonization targets and transitioning toward more sustainable energy systems.
- By conducting a social analysis and engagement with different stakeholder including consumers, policymakers, and industry leaders to know their perspectives this study will provide insights into societal attitudes toward biodiesel. Understanding these viewpoints can help address obstacles to its large-scale adoption and improve its social acceptability.

- The study will develop machine learning models to predict key factors such as biodiesel yield, production costs, and associated carbon emissions. This innovative approach will enhance the scientific methodologies used in biodiesel research and enable real-time decision-making to optimize feedstock selection and production processes.
- This research aligns with both global climate initiatives and local policies, such as the Punjab Government Act 2018, which advocates using waste cooking oil for biodiesel production. The study will offer actionable recommendations to support the adoption of biodiesel as a viable alternative fuel.
- By addressing challenges in biodiesel production and identifying scalable solutions, this research contributes to energy diversification and security. The findings will encourage the adoption of biodiesel as a renewable energy source, reducing dependency on fossil fuels and advancing sustainability goals.

1.4 Methodology of Research

The methodology of this research involves several sequential steps as shown in Figure 1.2 below aimed at evaluating biodiesel production from various feedstocks. The process begins with a comprehensive literature review to gather and synthesize existing knowledge on biodiesel production, characterization, life cycle assessment and use of advance techniques like biodiesel production for optimization of the supply chain for biodiesel production.

Next, the feedstock selection and preparation stage involves identifying diverse feedstocks, collecting suitable materials, and conducting pretreatment processes to prepare them for biodiesel production. These raw materials include used cooking oils, animal fats, and leftover vegetable oils.

After preparing the feedstock, biodiesel is produced using the most efficient and cost-effective method available. The process's efficiency and output are evaluated by measuring the yield.

The biodiesel produced is carefully analyzed to determine its properties. Techniques like Fourier Transform Infrared Spectroscopy (FTIR) and Gas Chromatography-Mass Spectrometry (GC-MS) are used to examine its chemical makeup. Key fuel characteristics such as flash point, specific gravity, and heating value—are also measured to ensure the fuel meets required quality standards..

The research will incorporates machine learning models to predict key parameters, including biodiesel yield, Fuel cost, and emissions. These models enhance the decision-making process by optimizing feedstock selection and production techniques.

A critical aspect of the study is the life cycle assessment (LCA) which evaluate the environmental impacts associated with biodiesel production and use. These assessments provide a comprehensive understanding of biodiesel's carbon emissions and its potential contribution to sustainable energy.

Lastly, the research includes a social analysis to examine the perspectives of stakeholders such as consumers, policymakers, and industry leaders regarding the adoption of biodiesel. This step ensures that the findings align with societal needs and address barriers to implementation.

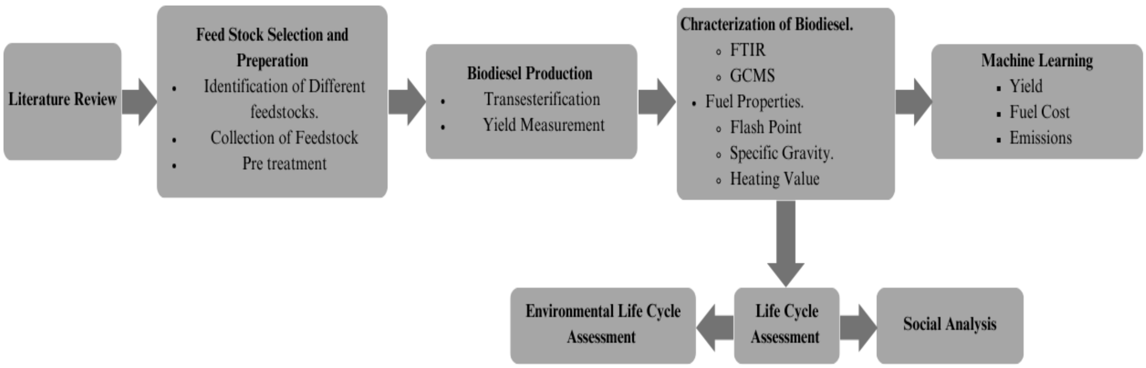


Figure 1.2 Methodology of Research

1.5 Scope of the research

This research provides an extensive evaluation of biodiesel production from various feedstocks, which contain vegetable oils, waste fats and used cooking oils. It focuses on key aspects such as biodiesel production, characterization, environmental impacts, and societal acceptance. The specific scope of the research is described below:

- The study examines biodiesel production using five distinct feedstocks to investigate how feedstock variability affects biodiesel yield and quality. The experimental phase includes evaluating properties such as Free Fatty Acid (FFA) content, heating value, specific gravity, and flash point to comprehensively investigate the properties of biodiesel.

- To gain deeper insights into biodiesel's chemical composition, the research utilizes advanced analytical techniques. These include Fourier Transform Infrared (FTIR) spectroscopy and Gas Chromatography-Mass Spectrometry (GC-MS), which provide detailed chemical and structural analysis of the biodiesel produced.
- The environmental LCA assesses the GHG Emissions and environmental impacts of biodiesel production throughout its lifecycle, from raw material acquisition to final use. System boundaries are clearly defined, and established methodologies for impact assessment are applied to quantify the environmental performance of each feedstock.
- The research investigates societal perceptions and stakeholder perspectives regarding biodiesel production. It focuses on consumer attitudes and policy implications. Surveys and qualitative methods are employed to gather insights from key stakeholders, including policymakers, industry leaders, and consumers.
- Machine learning is incorporated into research to develop predictive models for estimating biodiesel yield, production costs, and carbon emissions across different feedstock scenarios. This approach provides a data-driven framework for optimizing biodiesel production processes and improving decision-making.
- The study performs a comparative evaluation of biodiesel produced from different feedstocks to identify the most sustainable and efficient options. It also explores the advantages of blending various feedstocks to enhance production efficiency using machine learning and minimize environmental impacts.

1.6 Thesis outline

The distribution of the thesis is as follows.

1.6.1 Chapter 2: Literature review

This chapter provides a comprehensive review of existing research and studies related to biodiesel production, feedstock variability, biodiesel characterization, environmental life cycle assessments (LCA), and the integration of machine learning in energy research. Key gaps in the current knowledge are identified, establishing the foundation for the present study.

1.6.2 Chapter 3: Methodology

This chapter outlines the systematic approach taken to achieve the research objectives. It details the selection and preparation of feedstocks, the biodiesel production process, experimental methods for property characterization, and the techniques used for life cycle and social analysis. Additionally, it describes the development and implementation of ML models for biodiesel research.

1.6.3 Chapter 4: Experimental Results and Analysis

This chapter provides the experimental results obtained from the biodiesel production process. It includes a detailed analysis of biodiesel properties such as specific gravity, heating value, flash point. Comparative findings for the various feedstocks are also discussed, highlighting their impact on biodiesel yield and quality.

1.6.4 Chapter 5: Life Cycle Assessment and Social Analysis Results

Chapter 5 focuses on the results of the environmental LCA, evaluating the carbon emissions and overall environmental impact of biodiesel production for each feedstock. The chapter also presents findings from the social analysis, which investigates the perceptions of stakeholders, including consumers, policymakers, and industry representatives, regarding biodiesel adoption and its broader societal implications.

1.6.5 Chapter 6: Machine Learning in Biodiesel production

This chapter discusses the integration of machine learning models into Biodiesel research. It includes the development of predictive models for estimating biodiesel yield, production costs, and carbon emissions. The results from these models are analyzed to demonstrate their potential in optimizing biodiesel production processes and supporting decision-making.

1.6.6 Chapter 7: Conclusion and Recommendations

The final chapter summarizes the key findings of the research and their implications for biodiesel production, environmental sustainability, and policy development. Practical recommendations are provided for industry stakeholders, researchers, and policymakers. The chapter concludes by outlining potential areas for future research to further advance the field of biodiesel production.

Chapter 2 Literature Review

The global energy sector is undergoing major changes due to rising demand, technological progress, and environmental concerns. Renewable energy is expected to play a significant role in power generation, with projections indicating that over 35% of global electricity will come from renewables by 2025, according to the International Energy Agency (IEA)[11]. However, growing electricity demand, particularly in Asia, may lead to continued reliance on fossil fuels in some regions to meet peak energy needs. In the United States, natural gas is expected to account for 39% of power generation, a slight decrease from 42% in 2024, as renewable energy expands to meet increasing demand[12]. Despite the shift towards cleaner energy, fossil fuels remain essential for meeting peak power needs, particularly in countries like China and India. Global primary energy demand is projected to increase by more than 8 million barrels of oil equivalent per day in 2025 as shown in Figure 2.1, surpassing the growth of clean energy and contributing to higher greenhouse gas emissions[13].

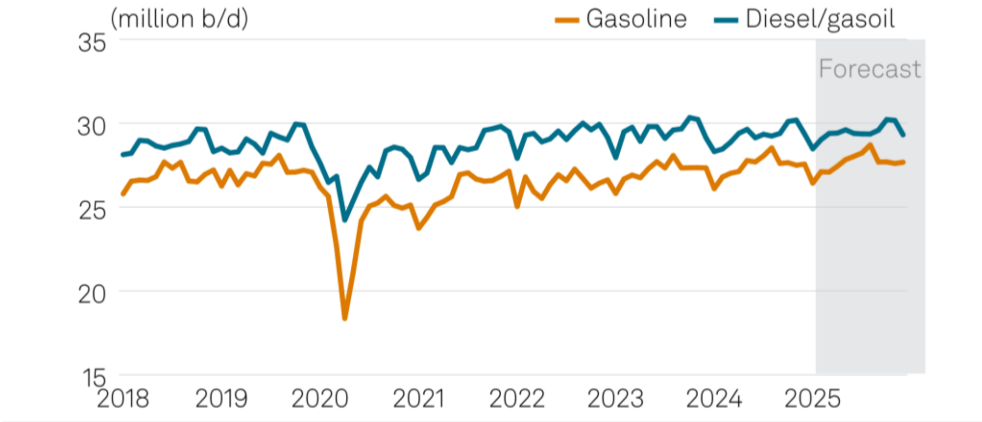


Figure 2.1 Forecast of Global Road Fuel Demand[13]

Pakistan's energy scenario is heavily reliant on fossil fuels, which have dominated the country's energy mix for decades. As of 2021, fossil fuels accounted for a significant portion of Pakistan's energy needs, with gas contributing 42%, oil 27%, and coal 17%. This reliance on fossil fuels has led to several challenges, including a severe energy crisis exacerbated by depleting domestic gas reserves and a heavy dependence on imported fuels[14], [15].

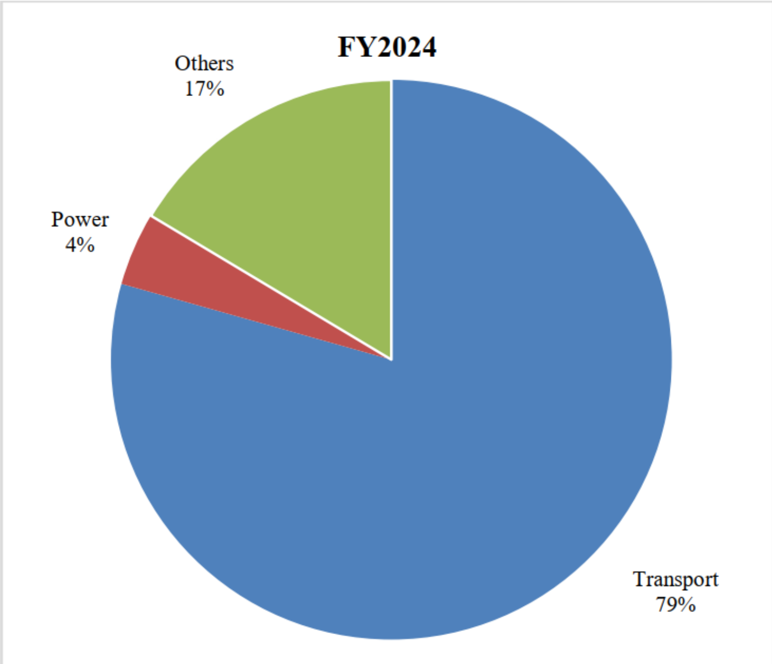


Figure 2.2 Sectoral Consumption of Petroleum Products[16]

In Pakistan, the transport sector is the largest consumer of petroleum products, making up about 79% of total usage, as shown in Figure 2.2. This heavy reliance on fossil fuels not only leads to environmental pollution and greenhouse gas emissions but also makes the energy sector vulnerable to global political tensions and unstable oil prices. As reported by the Ministry of Energy, Petroleum Division, from July to March of FY 2024, Pakistan imported nearly 11 million tonnes of crude oil and petroleum products at a cost of roughly $8.4 billion. Major imports included High-Speed Diesel (HSD), crude oil, and other petroleum products, with import quantities of 3,528.1 thousand tonnes, 1,233.5 thousand tonnes, and 6,169.3 thousand tonnes, respectively[16], [17].

2.1 Biodiesel as Sustainable Alternative

Biodiesel plays a vital role in this evolving energy scenario as a sustainable substitute for fossil diesel that helps lower greenhouse gas emissions while also improving energy security. It is produced from organic matter such as vegetable oils, animal fats, and waste cooking oils, making it a renewable energy source[12]. Biodiesel is increasingly recognized as a capable source of energy due to its potential to address both environmental and energy challenges. Derived from renewable sources such as agricultural waste and waste cooking oils, biodiesel offers a cleaner alternative to fossil fuels, contributing to reduced greenhouse gas emissions and enhanced energy sustainability. The integration of biodiesel into energy systems, particularly in small communities and smart grids, highlights its versatility and potential for localized energy solutions. It can an significantly reduce emissions of carbon monoxide, sulfur dioxide, nitrogen oxides, and particulate matter, contributing to improved air quality and climate change mitigation while Utilizing waste materials, such as agricultural residues and waste cooking oils, for biodiesel production minimizes waste and promotes a circular economy[18], [19]. The development of biofuels, including biodiesel, can enhance energy security by reducing dependency on fossil fuels and fostering economic development through job creation in rural areas[20]. While biodiesel presents numerous advantages, challenges such as competition for land, food security concerns, and the economic feasibility of large-scale production remain. Addressing these issues through sustainable practices and technological innovations is crucial for realizing the full potential of biodiesel as a sustainable energy source[21].

Biodiesel production has seen significant growth over the past two decades as countries aim to reduce their dependency on fossil fuels and mitigate greenhouse gas emissions. As of 2021, global biodiesel production reached around 13.97 billion gallons (52 million tonnes). The European Union (EU) remains the world's largest producer, accounting for nearly 50% of global biodiesel production, driven largely by policy incentives such as the Renewable Energy Directive (RED II)[22].

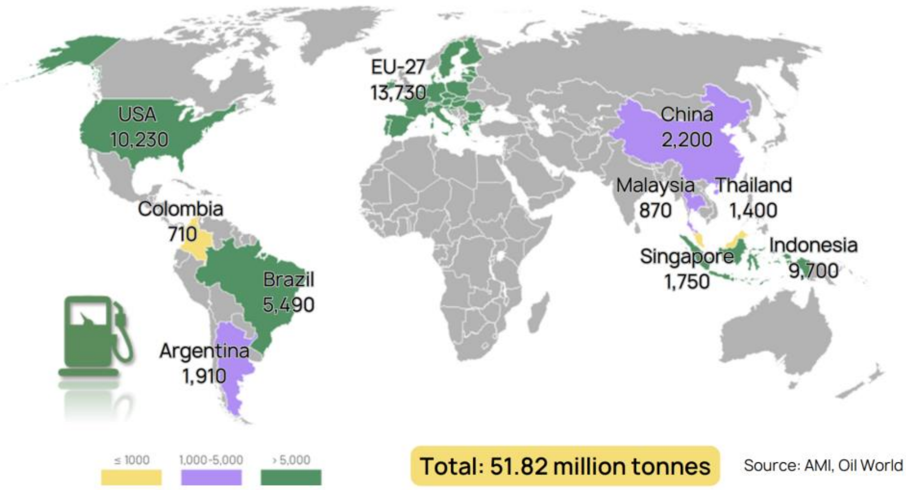


Figure 2.3 Biodiesel Production by Region[22]

In Southeast Asia, Indonesia and Malaysia are significant contributors to global biodiesel production, with palm oil being the main feedstock. However, the widespread use of palm oil has raised concerns about deforestation and environmental sustainability. Meanwhile, countries like China and India are increasingly exploring alternative feedstocks such as algae and jatropha[23].

Diesel fuel is widely utilized in Pakistan's agricultural sector to operate tubewells, tractors, and harvesting machinery. The country has around 1.2 million privately owned tubewells, with more than 60% relying on diesel. These diesel-operated tubewells consume nearly 3.5 billion liters of fuel annually, leading to an estimated 3.8 million metric tons of carbon dioxide emissions each year[24].

Biodiesel is a cleaner alternative that can help reduce the impacts of global warming by significantly lowering emissions. Depending on its feedstock and usage, burning one kilogram of biodiesel can reduce carbon dioxide emissions by approximately three kilograms. Its overall emissions are 65% to 90% lower than those from conventional diesel. Research shows that biodiesel produces fewer emissions throughout its lifecycle and can cut net CO_2 emissions by up to 78.45%. When blended at 20% with regular diesel (B20), it can reduce CO_2 emissions in urban buses by around 15.66%. Replacing petroleum diesel with biodiesel in urban transport systems can therefore contribute greatly to lowering carbon emissions[25].

2.2 Classification of Biodiesel

The European Academies Science Advisory Council (EASAC) classifies biodiesel into four categories based on feedstock type. First-generation biodiesel comes from edible oils, second-generation from non-edible oils, and third generation from waste oils. The fourth generation, known as solar biodiesel, utilizes synthetic biodiesel technology. This method is still in the early stages of research. Due to the high cost of feedstock for fourth-generation biodiesel, third-generation biodiesel, produced from waste cooking oil, is considered the most practical and cost-effective option[26].

Biodiesel production utilizes a diverse range of feedstocks, which can be broadly categorized into edible, non-edible, and waste materials. The choice of feedstock significantly influences the economical viability, sustainability, and environmental impact of biodiesel production. Edible oils such as coconut oil, palm oil, and soybean oil are frequently used in biodiesel production due to their high oil content and availability[27]. These oils are available readily and have well established supply chains, making them a reliable source for biodiesel production. The use of edible oils raises concerns about the food-versus-fuel debate, as it may impact food supply and prices[28], [29]. Non-edible oils are increasingly recognized as viable feedstocks for biodiesel production, offering a sustainable alternative to traditional edible oils. These oils, derived from plants that do not compete with food crops, can alleviate food security concerns while providing a cost-effective solution for biodiesel manufacturing. Non-edible oils are often cheaper than edible oils, reducing overall production costs, which can account for up to 75% of biodiesel expenses[30]. These oils can be sourced from plants that thrive in marginal lands, thus not impacting food supply chains[31]. Utilizing non-edible oils contributes to waste reduction and promotes renewable energy sources, addressing global warming concerns[31]. Different studies reveal that some non edible oils are common for its optimum yield and low cost. Hevea brasiliensis (Rubber Seed Oil) demonstrates high oil yield (52-63%) and meets biodiesel quality standards[32]. Jatropha curcas oil is widely studied for its efficiency and low emissions when used in diesel engines[33]. Ricinus communis (Castor Oil) Requires pretreatment to reduce free fatty acid content, achieving biodiesel yields of up to 96.2%[31].

First-generation biodiesel is produced from conventional food crops that contain high oil content. These feedstocks, including soybean oil, palm oil, rapeseed oil, and sunflower oil, are well-established sources for biodiesel production as shown in Table 2.1 below. While their availability and oil yields make them economically viable, their use for biofuel production has sparked debates due to competition with food crops. This competition raises concerns about land-use changes, food security, and environmental sustainability. The widespread use of these feedstocks has, in many cases, led to deforestation and other ecological consequences, making first-generation biodiesel both a solution and a challenge in the quest for cleaner energy.

Table 2.1 First Generation Biodiesel (Food-based Feedstocks)

Feedstock Type	**Key Characteristics**	**Advantages**	**Challenges**	**Ref**
Soybean Oil	High oil yield, widely available	Economically viable, well-established feedstock	Land-use concerns, deforestation in and competition with food crops	[34]
Rapeseed Oil	High oil yield, dominant in Europe	Suitable for colder climates, good biodiesel properties	Competition with food production, high cost in some regions	[35]
Palm Oil	High oil yield per hectare, widely	Economically efficient, large-scale production	Deforestation, loss of biodiversity, environmental concerns	[36]

	used in Southeast Asia			
Sunflower Oil	Moderate oil yield, used in North America and Europe	Less competition with food crops, moderate cost	Lower yield compared to soy or palm, limited scalability	[37]

Second-generation as shown in Table 2.2 biodiesel is derived from non-food-based feedstocks, such as waste oils, animal fats, and other byproducts that don't compete directly with food production. These feedstocks include tallow, poultry fat, used cooking oil (UCO), and waste animal fats. Since they are often waste products, their use for biodiesel offers an environmentally friendly solution that reduces waste. However, challenges remain regarding collection infrastructure, quality consistency, and the scalability of these feedstocks. Despite these hurdles, second-generation biodiesel represents a more sustainable approach compared to first-generation options, as it can repurpose waste materials and help reduce environmental pollution.

Table 2.2 Second Generation Biodiesel (Non-food feedstocks, including waste oils and fats)

Feedstock Type	**Key Characteristics**	**Advantages**	**Challenges**	**Ref**
Tallow	Derived from beef or mutton fat, high in saturated fats	Low-cost feedstock, available as waste byproduct	Poor cold-weather performance, higher saturation in biodiesel	[38]
Poultry Fat	Derived from chicken fat, high in saturated fats	Waste byproduct, inexpensive feedstock	Similar to tallow, cold-weather issues, poor biodiesel quality	[39]
Used Cooking Oil (UCO)	Recycled waste oil, typically from restaurants and households	Inexpensive, sustainable, reduces waste	Requires efficient recycling systems, quality variations	[40]
Waste Animal Fats	Recycled fats from food industries	Reduces food industry waste, eco-friendly	Requires collection infrastructure, quality variation	[41]

Third-generation shown in Table 2.3 biodiesel is produced from non-food feedstocks that are not only renewable but also more sustainable. This includes algae, jatropha oil, castor oil, camelina, and jojoba. Algae has garnered attention due to its high oil content and rapid growth, offering a potentially scalable solution that does not require fertile land. These feedstocks are often seen as the future of biodiesel production because they can be cultivated on marginal land and are not in direct competition with food crops. However, the major challenges for third-generation biodiesel lie in its high production costs, the need for efficient extraction technologies, and the slow commercialization of some crops.

Table 2.3 Third Generation Biodiesel (Algae and non-food crops)

Feedstock Type	**Key Characteristics**	**Advantages**	**Challenges**	**Ref**
Jatropha Oil	Non-edible oilseed, drought-resistant, grown on marginal land	Does not compete with food crops, can grow in arid regions	High initial investment, slow commercialization	[32]
Algae	High oil content, rapid growth	Very high potential yield per hectare, does not require fertile land	High production costs, scalability challenges, need for efficient extraction	[42]
Castor Oil	Non-edible, rich in ricinoleic acid, high oxidative stability	Good cold-weather properties, non-food crop, drought-resistant	Limited commercial-scale production, expensive cultivation	[43]
Camelina	Drought-tolerant, can grow on marginal lands	Sustainable, low input requirements	Limited market availability, low yield compared to other oils	[44]
Jojoba	Non-edible, drought-resistant, high oil content	High oxidative stability, suitable for arid climates	High initial investment, limited commercial-scale production	[45]

Waste cooking oil has emerged as a favorable feedstock for biodiesel production, proposing a sustainable alternative to conventional fossil diesels. The transesterification process, which converts triglycerides in WCO into biodiesel, has been extensively studied and optimized, demonstrating high conversion rates and favorable physicochemical properties.

A study was conducted by Suzihaque et al [46] has identified waste cooking oil as the most suitable feedstock for biodiesel production due to its low cost and favorable chemical properties. The transesterification process is commonly used to convert oil into biodiesel, with key factors such as reaction temperature, oil-to-methanol ratio, and catalyst selection playing a crucial role in optimizing production[46].

Xiangmei Meng[47] found that a conversion efficiency of 89.8% was achieved using a methanol-to-oil molar ratio of 9:1, with 1.0 wt% sodium hydroxide as a catalyst, at a temperature of 60°C for 90 minutes. Other experiments indicated that a methanol-to-oil ratio of 6:1 was more effective, producing biodiesel that met international standards[47].

Naresh successfully produced soybean-based biodiesel in 30 minutes, achieving a 90% biodiesel yield using a 6.1:1 oil-to-methanol molar ratio, a 611 kHz sound wave frequency, and ozone waves, demonstrating high efficiency within a short processing time[48].

Fangrui examined the current state of biodiesel production and noted its increasing attractiveness. However, high production costs continue to be a barrier to widespread commercialization due to challenges in process standardization and feedstock availability[49].

Innovative feedstocks like Algae and lignocellulosic biomass are being researched as future feedstocks due to their high yield potential and minimal land use requirements. Algae, in particular, is considered a promising third-generation biofuel feedstock due to its rapid growth and high oil content[50].

The optimal combination of process parameters, catalyst selection, and the impact of various feedstocks on biodiesel production remains a topic of ongoing discussion. These factors play a crucial role in minimizing carbon footprints. Table 2.4 offers a detailed review, highlighting key studies on biodiesel production, including conversion efficiency, variations across different feedstocks, alcohol-to-oil molar ratios, and catalyst choices. This table provides a comprehensive overview of the most significant advancements in the field.

Table 2.4: Review of different feed stocks and conversion efficiency for biodiesel production from waste oils.

Literature reference	**Feed stock**	**Production process**	**Alcohol to Oil molar Ratio**	**Catalyst Used**	**Conversion efficiency**
First Generation Feedstocks					
[51]	Palm Oil	Transesterification	5:1	KOH	62.55%

[52]	Crude Palm Oil	Transesterification	12:1	CaO	96.69%
[53]	Sludge Palm Oil	Enzymatic Transesterification	5:1	alginate-PVA lipase beads.	-
[54]	Soya Bean Oil	Transesterification	30:1	$Mo/Ce/TiO_2$	93.8%
[55]	Palm Oil	Transesterification	6:1	NaOH	92.8%
2nd Generation Feedstocks					
[26]	WCO collected from different sources	Both transesterification and esterification	-	H_2SO_4, KOH, ZeHPW, K_3PO_4	99%, 98.20%, 98.90%, 97.30%
[56]	Used Vegetable Oil	Esterification	19.8:1(Methanol to FFA molar ratio)	H_2SO_4	92%
[57]	Waste Cooking Oil	Transesterification using KM mixer	12:1	NaOH	97%
[58]	Waste Cooking Oil	Enzyme Catalyzed Transesterification	6;1	Thermomyces lanuginosus (TL) lipase	~90%
[59]	Dairy sludge	Non Catalytic transesterification	-	-	72–75.8 %
3rd Generation Feedstocks					
[60]	Caster Oil	Transesterification	18:1	Ca/C-500–3	95.44%
[61]	*Chlorococcum-Nannochloropsis* consortium.	One-step direct transesterification (OSDT)	-	-	70–71%
[62]	Caster Oil	Transesterification	12:1	ZnO/SnO_2	96.75 %

Various catalysts are used in biodiesel production, classified into two main types: heterogeneous and homogeneous. Catalysts which are homogeneous share the same phase as the reactants, while catalyst which heterogeneous in nature exist in a different phase. Most biodiesel today is produced through transesterification using homogeneous catalysts. These catalysts, which can be in liquid or gas form, are further divided into acid and base types. Acid catalysts like H_2SO_4 are typically used for esterification, while base catalysts such as NaOH and KOH are commonly applied in transesterification[58]. The benefits of homogeneous catalysts are as follows:

i. High conversion rate in a short period
ii. Freely available and other economic factors

Heterogeneous catalysts are in a different phase than the reactants and are commonly used in biodiesel production as solid catalysts. Examples include calcium oxide (CaO) and zinc oxide (ZnO). Studies have shown that using methanol as a reactant with CaO as a catalyst improves the conversion of waste cooking oil into biodiesel while maintaining fuel properties that meet ASTM standards. Osman et al. explored the role of computational chemistry and machine learning in biodiesel production, focusing on catalyst design, reaction efficiency, and waste feedstock utilization. The use of heterogeneous catalysts offers several advantages

i. Easy removal from biodiesel after reaction.
ii. The solid waste removed after biodiesel production can be reused or easily handled.

The selection of a catalyst plays a crucial role in the sustainability of biodiesel production. Homogeneous catalysts like KOH are highly efficient but generate wastewater and complicate the separation process, leading to a larger environmental impact[63]. On the other hand, heterogeneous catalysts are reusable, produce less waste, and simplify separation, making them a more sustainable option, especially for waste oil feedstocks. However, their lower catalytic activity may require higher energy inputs[64]. Advanced heterogeneous catalysts, such as single-atom catalysts (SACs), show potential for improving efficiency and sustainability in biodiesel production[65]. Despite their advantages, SACs face challenges such as metal atom agglomeration during fabrication and application due to their high surface energy, which can reduce both catalytic efficiency and stability[66].

2.3 Life Cycle Assessment of Biodiesel

Life Cycle Assessment (LCA) is an essential method for analyzing the environmental impact of biodiesel production from various feedstocks. It examines the entire process, from raw material extraction to production, distribution, usage, and disposal. This comprehensive evaluation provides a clear understanding of biodiesel's environmental effects and helps identify opportunities for improvement.

Gaidė et al[67] studied the life cycle assessment of biodiesel production using different alcohols and heterogeneous catalysts revealed varying environmental impacts. For example, using dolomite as a catalyst in the production of fatty acid methyl esters results in a lower global warming potential (1436.8 kgCO2eq t^{-1}) compared to eggshells and snail shells, which have higher impacts (2298.0 and 2266.1 kgCO2eq t^{-1}, respectively). Biodiesel derived from fish waste oil through the transesterification process has specific environmental impacts, with a global warming potential of 119.28 $kgCO_2eq$ per kilogram of biodiesel produced[68].

The environmental sustainability of biofuels, including biodiesel, is influenced by feedstock type, agricultural practices, and conversion technologies. Monte Carlo simulations reveal that biofuels can reduce greenhouse gas emissions by 45-60% compared to fossil fuels, but there is significant variability based on these factors[69].

The life cycle assessment (LCA) of biodiesel production from microalgae has been compared to petroleum-derived diesel to assess its environmental impacts. A study found that microalgae-derived biodiesel emits 1.48×10^{-1} kg CO_2 eq per MJ, which is higher than the CO_2 eq emissions of fossil diesel at 8.84×10^{-2} kg CO_2 eq. The primary sources of these emissions include electricity consumption, the required infrastructure, and yeast used in fermentation. To improve the sustainability of microalgae biodiesel, it is essential to focus on enhancing algae productivity and reducing electricity consumption, in addition to addressing the high emissions associated with yeast in the fermentation process[70][71].

A study on biodiesel production from *Jatropha curcas* L. seed oil in Pakistan assessed its large-scale environmental impact. Findings indicated that the production phase contributed significantly to emissions across all environmental impact categories. However, sensitivity analysis revealed that reducing fossil diesel use by 20% from the baseline led to a decrease in most environmental impact categories[72].

Comparative Life Cycle Assessment (LCA) study on biodiesel production from soybean, canola, sunflower, and palm oil in Indonesia found that the environmental impact of these feedstocks was higher than that of palm oil, particularly during the plantation stage[73]. Land use for cultivating multiple feedstocks contributed to greenhouse gas emissions of 9.89 tCO_2 per ton of biodiesel produced[73].

Life cycle assessment (LCA) of biodiesel plays a critical role in evaluating its sustainability by analyzing its environmental, social, and economic impacts throughout its entire production and use cycle. It examines key challenges such as the selection of biomass feedstocks, production technologies, and conversion processes. LCA serves as a valuable tool for policymakers by helping identify the most effective biodiesel options tailored to specific applications. This ensures that the chosen biofuels contribute to reducing greenhouse gas (GHG) emissions and mitigating environmental pollution while promoting the use of renewable energy. Recent studies within the LCA framework have explored various biodiesel feedstocks, focusing on their sustainability profiles and performance across different lifecycle stages[74].

A study on algal biorefineries, which included biodiesel, protein, and succinic acid production, demonstrated the importance of incorporating multiple products in assessing the environmental performance. This integrated approach can improve both the economic and environmental outcomes of algae-based systems. However, challenges such as high energy demand during protein extraction and the carbon losses associated with fermentation processes were identified as critical points for optimization[75].

A significant focus of LCA studies is the identification of "hotspots" in the biodiesel production process, where interventions can lead to significant environmental improvements. For example, a study comparing biodiesel production using different feedstocks found that algae-based biodiesel, despite its lower land use compared to crops like soybean, still faces challenges in terms of energy consumption during algae cultivation, harvesting, and oil extraction[76].

The social sustainability of biodiesel production is an essential yet often overlooked aspect when evaluating the overall impact of biofuels. Social Analysis has emerged as a powerful tool to examine the social impacts of biodiesel production along with the environmental impact, focusing on the well-being of stakeholders involved in the production process. These stakeholders include workers, local communities, and consumers, whose health, safety, working conditions, and economic benefits are closely tied to biodiesel production processes.

One of the primary concerns in biodiesel production is the working conditions, including labor rights, health, and safety of workers in feedstock cultivation and biodiesel processing plants. Studies show that regions where biofuels are cultivated can experience significant socio-economic impacts, both positive and negative. For instance, biodiesel production from feedstocks like soybean or palm oil has been linked to issues such as labor exploitation and poor working conditions, especially in developing countries[77]. Conversely, programs like the Social Fuel Stamp in Brazil aim to mitigate these impacts by incentivizing biodiesel producers to support family farmers and provide fair wages[78].

Furthermore, biodiesel policies have been found to create opportunities for rural development, with some studies suggesting that biodiesel production can improve employment rates and income distribution in marginalized regions[79]. However, the social impact of biodiesel production varies significantly depending on the feedstock used and the region. Biodiesel produced from non-food sources, such as waste oils or Jatropha, is less likely to compete with food crops, thus mitigating the "food vs. fuel" dilemma[80].

Social Life Cycle Assessment (S-LCA) allows for a detailed evaluation of the social risks and benefits across the entire life cycle of biodiesel production, from feedstock cultivation to fuel use. S-LCA studies often focus on indicators like labor rights, health and safety, fair wages, gender equality, and community engagement[81]. Brazilian biodiesel industry has used S-LCA to assess the impact of biodiesel policies on local communities and workers, revealing a need for more comprehensive social indicators that go beyond economic inclusion[78].

S-LCA can also assess the broader socio-economic impacts of biodiesel production. This includes factors like community engagement, local development, and gender equality. The integration of the Sustainable Development Goals (SDGs) into S-LCA frameworks is a growing trend, as it provides a more holistic approach to assessing the social sustainability of biodiesel[82].

The Table 2.5 below provides a comprehensive comparison of various studies focused on the environmental life cycle assessment (LCA) and social analysis of biodiesel. It is evident from the table that the majority of studies have utilized virgin oil for biodiesel production and conducted LCA based on literature-driven data. However, there is still a gap in real-world driven LCAs, which would provide more accurate insights. Regarding social analysis, most studies primarily concentrate on labor rights, gender equality, and job generation. Yet, there is a notable lack of perspectives from experts across different fields, as well as insights from consumers, which could offer a more holistic understanding of the social impacts.

Table 2.5 Summary of S-LCA and E-LCA from different studies

S.No	Ref	Objective/ Scope	Feedstock Used	Model Used for SLCA	Model used for ELCA	Environmental Impacts Studied	Social Impacts Studied	Product
1	[83]	Comprehensive assessment of the sustainability profile of synthetic fuels from agricultural waste through an integrated life-cycle analysis of environmental, economic and social evaluation.	Palm Waste	PSILCA	Recipe End Point 2016	Global warming, Fine particulate matter formation Terrestrial acidification, Freshwater, eutrophication Fossil resource scarcity	Child Labor, Contribution of the sector to economic development, Frequency of forced labor, Gender wage gap, Health expenditure, Women in sectoral labor force.	Biofuel
2	[84]	To perform a comprehensive life cycle assessment (LCA) of a biodiesel prototype derived from Jatropha curcas seeds oil in Pakistan	Jatropha curcas seed oil	Not Studied	SimaPro v.9.2 software using Eco-indicator 99 methodology	Carcinogens. Respiratory organics. Respiratory inorganics, Climate change. Ozone layer depletion. Eco toxicity. Acidification. Eutrophication. and fossil fuels.	Not Studied	Biodiesel
3	[85]	To evaluate and compare the environmental and social impact of two small-scale avocado biorefineries implanted in a rural area in the North of Colombia	Avocado	PSILCA	SimaPro 8.3 software	Climate change (CC). Terrestrial acidification. Human toxicity (HT). Photochemical oxidant. formation (POF). Particulate matter. formation (PMF). Freshwater ecotoxicity (FET). Agricultural land occupation (ALO). Water depletion (WD). Fossil depletion (FD).	Fair salary. Working time. Local employment.	Avocado Oil
4	[86]	To identify key hotspots in social sustainability that can inform the development of strategies and policies supporting sustainable palm oil biodiesel	Palm Oil	Survey	Not studied	Not studied	Human Rights. Working condition. Cultural heritage. Socio-economic. Repercussions. Governance.	Biodiesel
5	[87]	Development of Triple I and integrating with the LCSA framework which focused on vegetable oil-derived biodiesel.	Vegetable oil	-	Impact 2002+	Global warming potential. Human toxicity potential. Photochemical oxidation. Acidification. Eutrophication. Abiotic depletion.	human and indigenous rights. Working conditions. Cultural heritage. Poverty. Health and safety.	Biodiesel

						Ozone layer depletion. Terrestrial ecotoxicity.	Governance and political conflict.	
6	[88]	Development of a novel assessment tool, named the GreenZee model, to reflect the social impacts	-	GreenZee Assessment tool	-	-	Human rights (HR) Working conditions (WC) Society/health and safety (HS) Cultural heritage (CH) Socioeconomic repercussions (SR)	Biodiesel
7	[89]	To evaluate the sustainability of palm oil (CPO) as a raw material for biodiesel production from environmental, social, and economic perspectives and to propose recommendations for a sustainable palm oil biodiesel policy strategy.	Crude Palm Oil	Surveys	Literature references	Greenhouse gas parameters. Use of fossil fuels, Acidification. Eutrophication. Carcinogenic effects.	Human rights. Working conditions. Cultural heritage. Socio-economic impacts, and governance.	Biodiesel
8	[90]	To analyze the feasibility, risks, and opportunities of current methods for measuring social impacts at the company level.	Algae	Surveys	-	-	Workers group: Consumer group: Local community group:	Biomass
9	[91]	To evaluate the multidimensional effects of transportation systems and apply multi-criteria decision-making (MCDM) to assess the sustainability of alternative fuels.	Vegetable Oil	Surveys	-	GHG emissions. Air pollutants (NOx and PM emissions). Noise.	Employment. Social benefits. Social acceptability.	Biodiesel
10	[92]	To perform a comprehensive environmental and economic sustainability assessment of alternative fuels and powertrains in the transport sector.	-	-	Simapro software Recipe midpoint (H) and Recipe endpoint (H) methods.	Climate change, Freshwater. Eutrophication. Marine eutrophication. Human health Photochemical oxidant and Particulate matter formation. Freshwater and Marine eco-toxicity. Agricultural land. Urban land occupation. Water depletion and fossil depletion.	-	Biodiesel

2.4 Machine Learning in Biodiesel Production

Machine learning (ML) is increasingly recognized as a transformative tool in biodiesel production, enhancing efficiency, yield, and sustainability. By leveraging advanced algorithms and tools, researchers can optimize various parameters and supply chain in biodiesel production processes, leading to improved operational outcomes.

One of the primary applications of ML in biodiesel production is the development of predictive models for optimizing reaction conditions and improving biodiesel yield. Artificial neural networks (ANN) and adaptive neuro-fuzzy inference systems (ANFIS) are the most widely used ML techniques for this purpose. ANN model developed by Moradi et al. was used to predict biodiesel yield from soybean oil using KOH as a catalyst, achieving an R^2 value of 0.99[93]. Similarly, ANFIS models have been applied to predict biodiesel yield and optimize the transesterification process, often in combination with global optimization algorithms such as genetic algorithms (GA) and particle swarm optimization (PSO)[93].

Other popular algorithms include decision trees (DT), random forest (RF), and K-nearest neighbor (KNN). These methods have been employed for tasks such as predicting biodiesel fuel properties, including viscosity, flash point, and cetane number, as well as optimizing the production process. The flexibility of ML models in handling diverse feedstock types, ranging from edible oils like soybean and palm oil to non-edible oils such as Jatropha and waste cooking oils, has further increased their utility[94].

Vellaiyan. S et al. used ML models to predict critical output properties such as biodiesel yield, purity, and chemical composition, enabling real-time monitoring and control of the process. For example, in the transesterification process, ANN has been used to predict biodiesel yield based on operating conditions like temperature and methanol/oil molar ratio [95]. While selecting feedstock algorithms like RF and SVM have been used to predict biodiesel quality based on feedstock characteristics such as fatty acid composition, iodine value, and viscosity[95].

Optimization involves the fine-tuning of several process parameters, including the molar ratio of methanol to oil, reaction temperature, catalyst concentration, and reaction time. A study by Ishola et al. ANFIS coupled with GA was used to optimize the esterification process, resulting in a significant reduction in free fatty acid (FFA) content and improved biodiesel yield[96].

Machine learning techniques have also been used to predict the environmental impact of biodiesel production. These models evaluate the carbon footprint, energy consumption, and emissions associated with different biodiesel production pathways[97].

2.5 Summary

To summarize the literature review there is a lot of work available on biodiesel production, characterization, sustainability assessment, and use of machine learning for the optimization of biodiesel production. Despite extensive research on biodiesel production from various feedstocks focused on the experimental evaluation, there is a lack of comprehensive studies that assess the environmental life cycle of different biodiesel sources using real-world data from experiments, as most existing research relies on literature-based assessments. Additionally, limited studies integrate stakeholder engagement to evaluate the social dimensions of biodiesel production alongside environmental life cycle assessment and experimental investigation of biodiesel characterization. This study addresses these gaps by conducting an experimental investigation and characterization of biodiesel for benchmarking, followed by the use of experimental data for life cycle assessment. It also incorporates social analysis by gathering insights from key stakeholders to assess the broader impacts of biodiesel production. Furthermore, this research applies machine learning techniques, specifically artificial neural networks, to predict fuel yield, emissions, and cost per liter based on a blend of feedstocks.

Chapter 3 Methodology

This chapter outlines the experimental methods and techniques used to analyze and evaluate biodiesel produced from various feedstocks, within the framework of a life cycle assessment (LCA). The study begins with the selection of different feedstock sources, followed by their conversion into biodiesel through the transesterification process. Key parameters, including reaction temperature, catalyst concentration, and reaction time, were carefully controlled to ensure the production of high-quality biodiesel.

To examine the chemical composition of the biodiesel samples, Fourier-transform infrared spectroscopy (FTIR) and gas chromatography-mass spectrometry (GC-MS) were used, providing detailed insights into molecular structure and functional groups. Additionally, physicochemical properties such as viscosity, density, flash point, and acid value were measured for further characterization.

The LCA methodology in this research assesses the environmental impact of biodiesel production, transportation, and use, while also incorporating a social analysis to evaluate the socio-economic implications. Furthermore, machine learning techniques were applied to optimize the biodiesel supply chain by predicting production costs, yield, and emissions. This combined experimental and computational approach offers a comprehensive evaluation of biodiesel sustainability across various feedstocks, considering environmental and social factors.

3.1 Biodiesel Production

According to the American Society for Testing and Materials (ASTM), biodiesel consists of alkyl esters formed through the transesterification of triglycerides with alcohol in the presence of a catalyst. When potassium hydroxide (KOH) is used as a catalyst, glycerol is produced as a byproduct, which can be utilized in industries such as soap manufacturing and fertilizers, where it serves as a dust suppressant[98]. However, high free fatty acid (FFA) levels and water content in waste cooking oil pose challenges in biodiesel production, making the process more complex. To address these issues, a two-stage transesterification process is preferred for large-scale biodiesel production, as it improves efficiency and ensures better fuel quality[26].

Methodology for Biodiesel production involves feedstocks selection, sample analysis, transesterification, esterification(if required) washing and post treatment of biodiesel. Esterification and transesterification reaction depends on the percentage of FFA in oil. FFA acids depends on the quality of cooking oil and the frequency of cooking oil used. The FFA value of oil increases with the increase in use of oil. If the FFA>2% esterification is done and if FFA<2% transesterification is carried out.[57] The chemicals involve the esterification and transesterifications are H_2SO_4, Methanol, Phenolphthalein, NaOH, Isopropyl alcohol, and waste cooking oil.

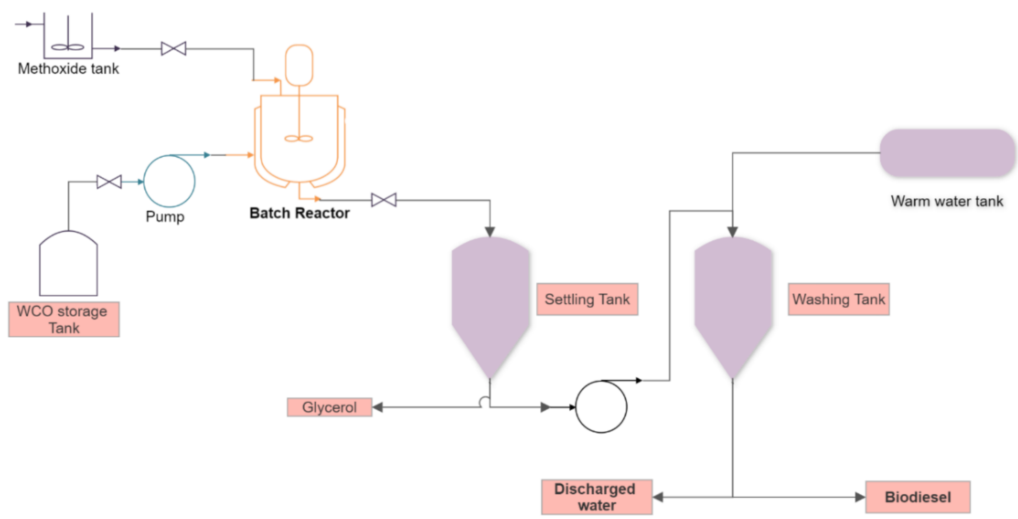


Figure 3.1 Schematic Diagram for Biodiesel production

The schematic diagram in the above Figure 3.1 illustrates the biodiesel production process using waste cooking oil. Initially, the oil is filtered through a strainer or filter paper to remove solid impurities. It is then pumped into the reactor tank for the transesterification process. The methoxide tank, containing methanol and a catalyst, supplies the necessary reactants to the reactor tank. Equipped with a heater and stirrer, the reactor tank ensures continuous mixing and heating of the oil and methoxide for 60 minutes at 60°C. Once the reaction is complete, the biodiesel mixture is transferred to a settling tank, where it rests for 2–3 hours to allow the separation of glycerol. The glycerol is then removed, and the biodiesel is pumped into a washing tank. In the washing tank, warm water is added to eliminate impurities, excess methanol, and residual catalyst. After multiple washes, the biodiesel is dried at 100°C to remove any remaining water content, making it ready for use.

3.1.1 Feedstock selection

Various feedstocks are utilized for biodiesel production, with selection often based on availability. In this study, four distinct feedstocks were chosen for analysis, including waste cooking oils, a mixture of oils and fats, chicken feather oil, and palm oil.

Samples of waste cooking oil were gathered from various sources, including frying restaurants and local hotels. These establishments used the oil for frying different foods such as meat, poultry, and fries. The collected samples came from a range of locations in Islamabad, Pakistan, including both local eateries and high-end five-star restaurants, as detailed in the Table 3.1 below. Since the used oil contained suspended particles, filtration was necessary before using it for experimentation[99] The process of converting the oil into biodiesel involves several steps: preheating, esterification (if needed), transesterification, washing, and post-heating to remove water and excess methanol[100]. Samples collected from different sources have distinct properties including the FFA value.

Table 3.1 Different types of feedstocks used for Biodiesel production

Type of Feedstock	Code Used for Reference	Sima Pro Representation
Feedstock from a five start Brand	Type-A	Scenario-3
Feedstock from three start Brand	Type-B	Scenario-5
Palm Oil	Type-C	Scenario-2
Chicken Feather Oil	Type-D	Scenario-1
Fossil Diesel	-	Scenario-4

3.1.2 Sample Analysis

Prior to biodiesel production, it is crucial to conduct sample analyses, such as determining the acid value and free fatty acid (FFA) content. These analyses help ensure that the appropriate process parameters are selected and optimized, while maximizing the yield of biodiesel. The chemical properties of WCO derived from canola cooking oil are given below on the Table 3.2.

Table 3.2 Properties of Waste Cooking Oil

Test	**Result**
Acid Value	7.2
Soap	Nill
PH	5.5
Iodine Value (IV)	98
Density	0.916 at 30ºC
Impurities	1%
Appearance	Light Brown color
Saponification	194.1
Sulphur	9.28ppm

The acid value represents the amount of potassium hydroxide (KOH) required to neutralize the free fatty acids (FFA) in waste cooking oil. It is determined using the titration method through the following steps:

i. Measure the acid value and FFA percentage using KOH.
ii. Calculate the additional catalyst needed for the transesterification process.
iii. Mix 1 mL of oil with 10 mL of isopropyl alcohol and add a few drops of phenolphthalein indicator.
iv. Add the titrant until the solution turns purple.

The acid value and FFA percentage are determined using the given equation. The additional NaOH required is based on the volume of titrant used to titrate 1 mL of oil. To determine the total catalyst amount for conversion, extra NaOH is added at a concentration of 4.5 g/L.

$$Acid\ Value = \frac{volume\ of\ titrant\ in\ ml \times Normality\ of\ KOH \times atomic\ mass\ of\ KOH}{mass\ of\ oil} \quad \text{Equation 3.1}$$

$$FFA(\%) = \frac{Acid\ value}{2} \quad \text{Equation 3.2}$$

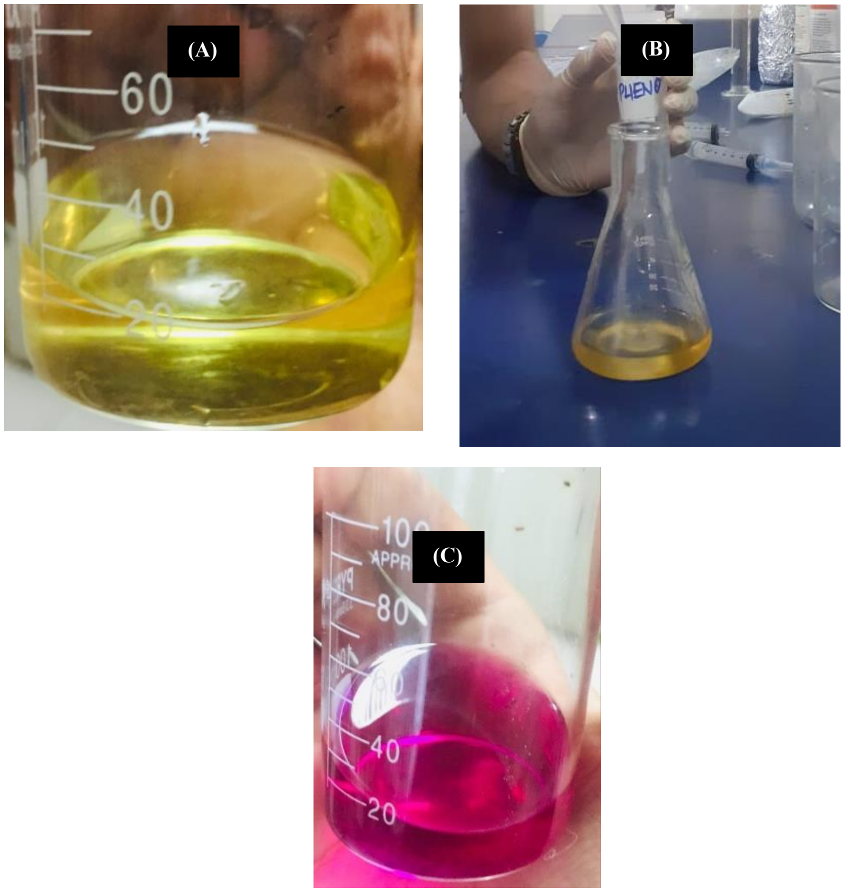


Figure 3.2 A) Addition of Oil to Isopropyl B) Addition of Indicator to solution C) Change in color after addition of titrant solution

3.1.3 Pretreatment of Feedstock

Once the acid value of the sample is determined, the oil undergoes a pretreatment process. The pretreatment involves filtering the oil to remove any solid contaminants. Filtration can be accomplished using a strainer or filter, depending on the size of the particles present. After filtration, the oil is subjected to a heating process. The primary purpose of heating is to eliminate any suspended water particles within the oil. If water remains in the oil and the transesterification process proceeds, it can result in the formation of soap instead of biodiesel. To prevent this, the oil is heated to approximately 100°C for a specific duration, depending on the oil quantity, to remove and evaporate the water content effectively.

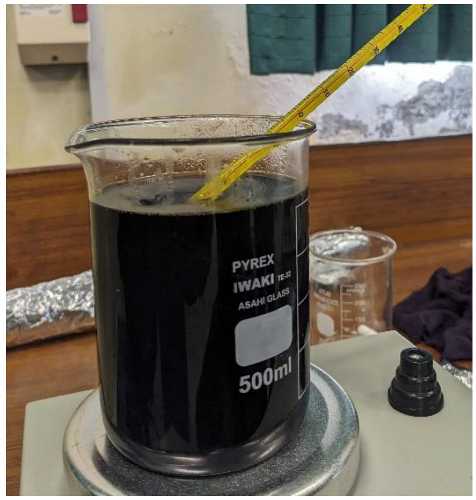


Figure 3.3 Heating of Oil

3.1.4 Different methods used for Production of Biodiesel

The primary purpose of using different techniques for biodiesel production is to reduce the viscosity of the cooking and extract the desired product. To prevent the direct use of cooking oil in compression ignition (CI) engines, various techniques are applied to lower its viscosity and convert it into biodiesel. The high viscosity of cooking oil can lead to gum formation in the injection system and combustion chamber, affecting engine performance and efficiency[101]. There are several methods which are used for production of biodiesel to deal with the high viscosity of vegetable oils as fuel[102]. However, there are four major techniques that are employed for biodiesel production (as shown in figure) include the direct use and blending of raw oils[103], micro emulsion[104], thermal cracking[36] and transesterification. Each process has its own advantages and drawbacks, as illustrated in the Figure 3.4 below.

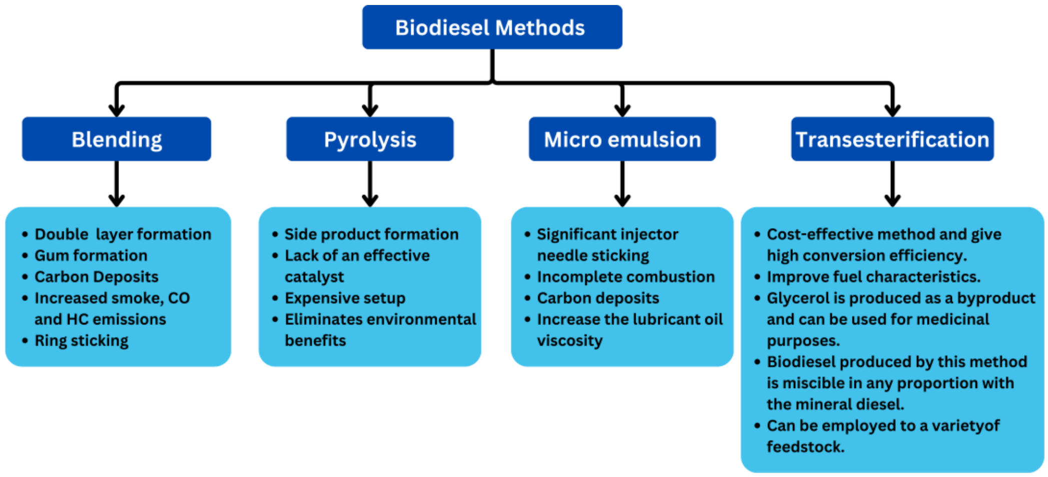
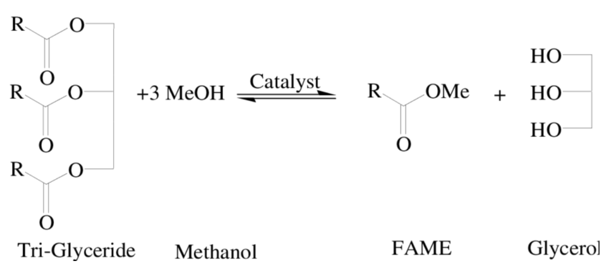


Figure 3.4 Different Methods used for Biodiesel Production

3.1.5 Transesterification reaction

Transesterification is one of the most effective methods for biodiesel production[105]. When the free fatty acid (FFA) content is below 2%, transesterification can be performed directly, also known as base transesterification[46]. However, if the FFA content exceeds 2%, esterification must be carried out as a pretreatment step to prevent soap formation. This pretreatment process involves the use of H_2SO_4 and methanol[106]. Figure *3.6* illustrates the step-by-step flowchart of the transesterification reaction, where methanol is mixed with oil in the presence of a catalyst at a specific temperature. Due to their low cost and easy availability, NaOH and KOH are widely used as catalysts [103]. The oil sample is first heated to 60°C, after which methanol is added along with the catalyst. The mixture is continuously stirred for 30 minutes using a mechanical stirrer. Additional catalyst is required to neutralize the FFA content. For optimal conversion of cooking oil to biodiesel, a methanol-to-oil ratio of 1:5 is used [107]. Once the methoxide is mixed with the pretreated oil, the reaction proceeds for 60 minutes.

Equation 3.3 Transesterification Reaction



3.1.6 Separation

After the transesterification process, the mixture was transferred to a separation vessel and allowed for settling for a specific duration at room temperature. During this time, two distinct layers formed within the mixture. The denser glycerol layer settled at the bottom, while the lighter biodiesel layer floated at the top. To facilitate the efficient removal of the glycerol, the vessel utilized a conical bottom design. The suggested conical design for the separation of mixture support the easy separation of the glycerol layer from the biodiesel, minimizing biodiesel loss during the process.. As glycerol is denser than biodiesel, the separation was achieved by carefully draining the glycerol from the bottom of the vessel.

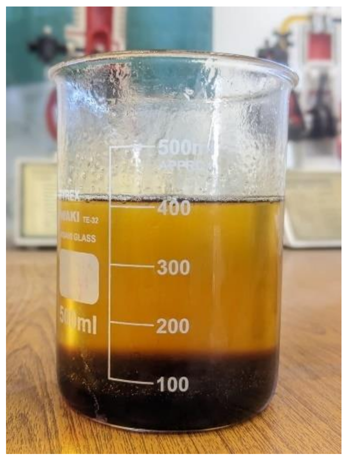


Figure 3.5 Settling of glycerol

3.1.7 Washing

After glycerol is separated, the biodiesel is washed with warm water to eliminate impurities, residual catalyst, and any soap traces. The washing process is repeated three times to enhance purity and improve the color of the biodiesel. Inadequate washing can leave behind soap residues and other contaminants, which can negatively impact both the color and quality of the biodiesel, making it essential to meet standard specifications.

3.1.8 Post heating

After washing, biodiesel may still contain water and residual methanol, which must be removed to maintain its optimal PH. Excess methanol can affect the pH balance and cause engine issues during use. Heating the biodiesel to 110°C helps evaporate both water content and any remaining methanol, ensuring better fuel quality.

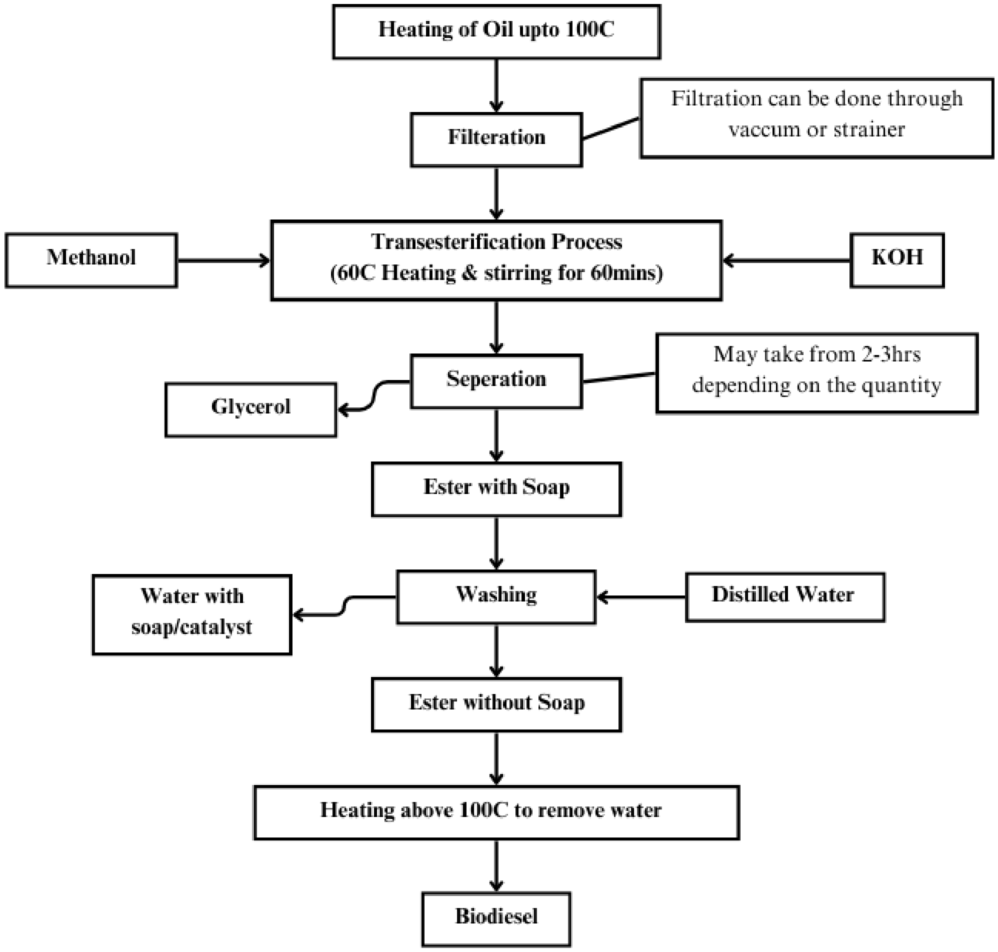


Figure 3.6 Flow sheet of Transesterification Reaction

3.2 Physio chemical Properties

The physicochemical properties of biodiesel were analyzed following ASTM (American Society for Testing and Materials) standards to ensure accuracy and consistency. The key properties assessed included lower heating value, flash point, and specific gravity.

3.2.1 Heating Value

The heating value refers to the amount of heat generated when a unit volume of fuel is combusted. It is expressed in MJ/kg or KJ/g. The calorific value of the samples and various biodiesel blends was measured using an oxygen bomb calorimeter, SMT-HT-54, as shown in the Figure *3.7*.

The heating value (HV) of fuel plays a crucial role in determining engine power. A fuel with a lower heating value will have higher consumption compared to one with a higher heating value at the same power output [108]. Biodiesel contains less carbon and hydrogen than diesel, resulting in a lower HV[108]. The presence of chemically bonded oxygen further reduces biodiesel’s heating value[109]. When the proportion of biodiesel increases in a blended fuel (biodiesel mixed with diesel), the calorific value decreases. The heating values of different biodiesel blends were measured using a bomb calorimeter and compared to the heating value of mineral diesel, which is 43.96 MJ/kg[110][111]. A bomb calorimeter determines the heat of combustion by burning the sample in a sealed chamber filled with pure oxygen. This method provides a simple and cost-effective way to measure the energy content of hydrocarbon fuels. Combustion occurs under high oxygen pressure, up to 16 bars, to ensure complete combustion.

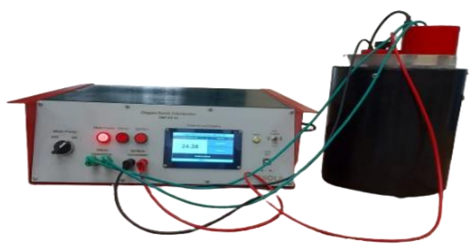


Figure 3.7 Oxygen Bomb Calorimeter

Figure 3.8 Different Samples of Biodiesel

3.2.2 Flash Point

The flashpoint(FP) of a fuel is the minimum temperature at which enough evaporated fuel vapors are present for combustion to occur after an ignition source (spark or flame) is supplied[112].

The flash point (FP) of biodiesel is determined using the ASTM D93 standard with the Pensky-Martens Closed Cup method. In this process, a metal test cup of specified dimensions is filled with the test specimen up to the inner mark and sealed with a designated lid. The sample is then heated and stirred at controlled rates using one of three defined procedures (A, B, or C). At regular intervals, an ignition source is introduced into the test cup while stirring is paused. The flash point is recorded as the temperature at which sufficient vapors accumulate and ignite upon exposure to the ignition source[113].

3.2.3 Specific Gravity

Specific gravity (SG) is the ratio of a material's density to that of water. The ASTM D1298 standard test method is used to determine specific gravity using the hydrometer method. Biodiesel's specific gravity was measured following ASTM D1298, which outlines the procedure for determining the SG of biofuels[114].

3.3 Characterization of Biodiesel

Biodiesel characterization was conducted using two advanced analytical techniques: Gas Chromatography-Mass Spectrometry (GC-MS) and Fourier Transform Infrared Spectroscopy (FTIR). GC-MS was used to analyze the chemical composition of biodiesel by identifying individual components and assessing fatty acid methyl esters (FAMEs). Meanwhile, FTIR spectroscopy provided insights into the molecular structure and functional groups, helping to verify the quality and purity of the biodiesel.

3.4 FTIR Analysis

Fourier Transform Infrared (FTIR) spectroscopy is an analytical technique which is used to Recognize functional groups in various sample forms, including liquids, solutions, pastes, powders, and gases[115]. In FTIR analysis, energy is emitted from the source and passes through an aperture that regulates the amount of energy reaching the sample. The beam then enters the interferometer before being transmitted through the sample. As the beam interacts with the sample, a detector captures the interferogram signal. These signals are then digitized and processed by a computer, where a transformation occurs, generating the final spectrum for further interpretation[116].

IR spectroscopy is a highly effective method for identifying the functional groups within a sample. The IR spectrum is categorized into three wavelength regions: the far-IR region, which begins beyond 400 cm^{-1}; the mid-IR region, ranging from 400 cm^{-1} to 4000 cm^{-1}; and the near-IR region, spanning from 4000 cm^{-1} to 13,000 cm^{-1}. Among these, the mid-IR spectrum is the most commonly used for sample analysis. However, the fingerprint region (600 cm^{-1} to 1500 cm^{-1}) is challenging to interpret, making it unsuitable for identifying unknown compounds [117].

The mid-IR spectrum is divided into different regions:

i. Single bond region (2500cm^{-1}-4000 cm^{-1})
ii. Triple bond region (2000cm^{-1}-2500 cm^{-1})
iii. Double bond region (1500cm^{-1}-2000 cm^{-1})

3.5 GCMS analysis

Gas Chromatography-Mass Spectrometry (GC-MS) serves as an essential analytical tool for determining the chemical composition of biodiesel, particularly for identifying the fatty acid methyl esters (FAMEs) present in biodiesel samples. The analysis involves a series of well-defined steps, including sample preparation, instrumental setup, GC-MS analysis data interpretation and comparison.

3.5.1 Sample Preparation

To prepare the biodiesel sample for GC-MS analysis, a portion of the biodiesel is dissolved in a suitable solvent, such as hexane or ethyl acetate, to bring the concentration within the linear range of the instrument. The solution is then filtered through a 0.45 µm syringe filter to eliminate any particulate matter that might interfere with the chromatographic separation and analysis [118].

3.5.2 GC-MS Analysis Setup

The GC-MS setup consists of two main components: the gas chromatograph (GC) and the mass spectrometer (MS). For the analysis of biodiesel, a polar capillary column, such as DB-Wax or BPX70, is employed for separating the individual FAMEs. The gas chromatograph is equipped with an automatic injector that can operate in either split or splitless mode, depending on the sample and desired sensitivity. The injector temperature is set to 250°C to 270°C, with a carrier gas such as helium or hydrogen being used at a flow rate of 1–2 mL/min, which ensures an optimal separation of the components within the biodiesel sample [119], [120].

The oven temperature program is an essential aspect of the GC-MS method. The temperature starts at 60°C, held for 1–2 minutes to allow for initial sample vaporization.

The temperature is then increased at a rate of 10°C/min to 280°C, where it is maintained for an additional 10–15 minutes to ensure the complete separation of the various components.

The mass spectrometer is typically operated in Electron Impact (EI) ionization mode, as this method produces consistent and reproducible fragmentation patterns that are key to compound identification. The mass spectrometer scans the mass-to-charge ratio (m/z) range from 50 to 600, capturing ions across a broad spectrum to identify the molecular structures of the compounds present in the biodiesel sample. The ion source temperature is set between 230°C and 250°C to ensure efficient ionization.

3.5.3 GC-MS Analysis Procedure

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3.5.4 Data Analysis

Analysis was performed by comparing the retention times and mass spectra of the observed peaks with reference libraries, such as the NIST Mass Spectral Library. In biodiesel analysis, the primary constituents are typically FAMEs, but other components, such as residual methanol or glycerol, may also be detected and identified.

3.6 Environmental Life cycle Assessment

Environmental Life Cycle Assessment (LCA) is a systematic method for assessing the environmental impacts of a product at every stage of its life cycle, from raw material extraction to end-of-life disposal. For biodiesel, LCA assesses the environmental effects of its production, transportation, and usage, taking into account factors such as resource consumption, emissions, and energy efficiency.

This study utilizes Environmental Life Cycle Assessment (LCA) to evaluate the impact of biodiesel production from multiple feedstocks. The analysis examines the potential environmental effects across various impact categories. Specifically, the assessment focuses on the impact on ecosystems, human health, and resource depletion..

3.6.1 Methodology for E-LCA

The Life cycle analysis used in this study is divided into various steps and is based on ISO14040 framework[121]. The secondary data was taken from the Ecoinvent data base from the Simapro 9.5.02 software and the primary were taken from the experiments. The study is divided into four stages.

- Goal and scope definition.
- Inventory analysis.
- Impact Assessment.
- Interpretation.

3.6.2 Goal and scope definition

The goal of this study is to assess the environmental performance of biodiesel production derived from various feedstocks, including Waste Cooking Oil (from diverse sources), Chicken Feather Oil, and Crude Palm Oil, with a comparative analysis to fossil diesel. The study adopts a comprehensive life-cycle approach, assessing the environmental impacts of biodiesel production from the collection of raw materials to its consumption in diesel engines. This approach offers an in-depth comparison of the environmental effects linked to each biodiesel feedstock.

This analysis covers the entire biodiesel production process, starting with the collection of feedstocks and extending through to the final consumption of the biodiesel. A cradle-to-grave (collection stage to end use) analysis methodology is employed, encompassing the entire lifecycle from the raw materials, through biodiesel production, transportation, and its use in agricultural and industrial engines (such as tractors and petter engines). This comprehensive evaluation ensures a robust examination of the environmental impacts across every phase of biodiesel production.

The biodiesel manufacturing process consists of several key stages: sourcing raw materials from local restaurants or factories, transporting these materials to the processing site, pretreatment of the feedstocks, followed by transesterification washing and Post heating. Once produced, the biodiesel is then transported to its point of end use. Glycerol is the byproduct of biodiesel production which can be used as useful product for soap production as well as ether production which may serve as fuel additive for enhance the combustion efficiency while reduce the emissions[122]. Wastewater can be used for the irrigation purpose after appropriate filtration. Crude glycerol after purification can be also used for medical applications while unreacted methanol can be recovered [123].

In this study, the functional unit is defined as the production of 1 liter of biodiesel from various feedstocks, ready for use. This standardized unit facilitates a direct environmental comparison of biodiesel produced from different sources. The system boundary for this analysis is clearly outlined, detailing each stage of the biodiesel production process from raw material collection to its final consumption, as illustrated in the Figure 3.9 below.

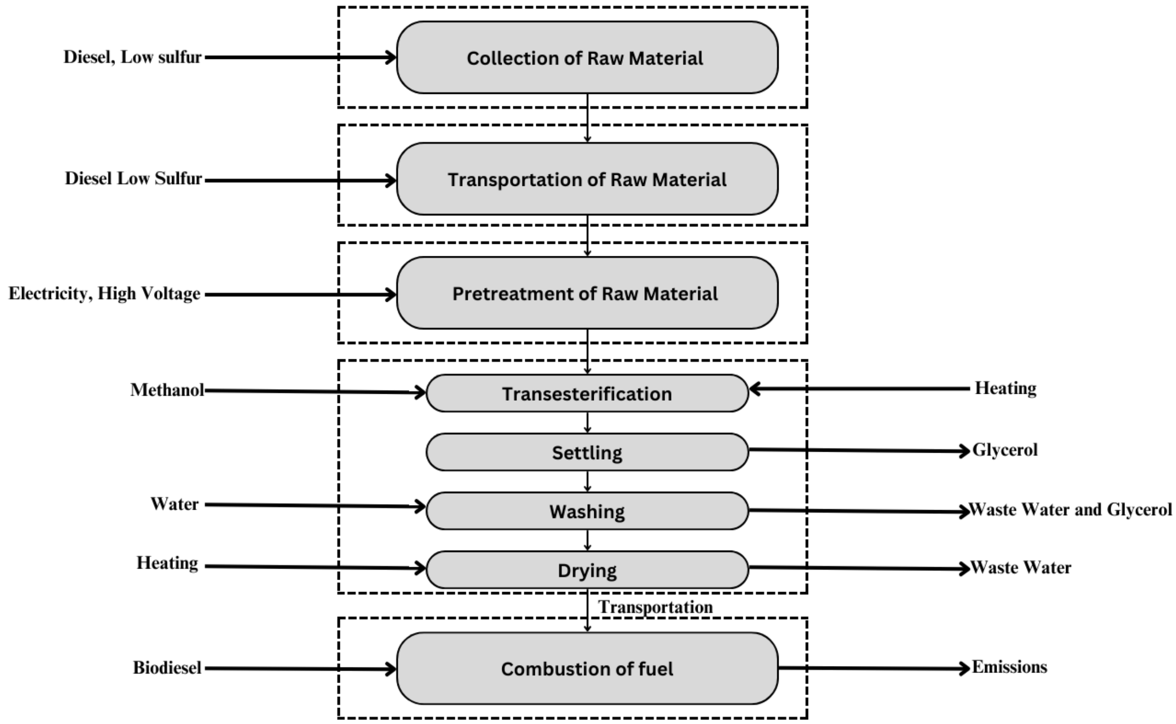


Figure 3.9 System Boundary definition for LCA

3.6.3 Life cycle Inventory Analysis

In this study, Life Cycle Inventory Analysis (LCIA) was performed to evaluate the environmental impact of producing 1.0 liter of biodiesel from various feedstocks. Real-time data on material and energy inputs, along with waste generation, were considered throughout the biodiesel production process. Three scenarios were modeled in Simapro V9.5.0.2 to compare different feedstocks and their environmental performance against fossil diesel. Material and energy inputs were carefully analyzed, and waste outputs were quantified to provide a comprehensive assessment of biodiesel's environmental footprint. The collected Life Cycle Inventory data was systematically tabulated in Table 3.3 below

Table 3.3 Inventory of LCA

Parameter	Unit	Quantity			
		Scenario 1	Scenario 2	Scenario 3	Scenario 5
Collection of Oil from different Hotels					
Transport	kgkm/Feedstock Transported	24.44	64.3	21.6	64.33
Raw Material	L/ Time Period	50	200	160	200
Out Put					
Oil/Feedstock Per Batch	L	80	74.29	61.18	69.33
Pre-Treatment					
Electricity	KWh/L	0.066	0.061	0.049	0.054
Feedstock	L	80	74.29	61.18	69.33
Transesterification					
Electricity	KWh/L	0.05	0.05	0.05	0.05
Feedstock	L	80	74.29	61.18	69.33
KOH	g/L	0.0125	0.0115	0.011	0.0117
Methanol	kg/L	0.15	0.15	0.15	0.15
Transport	kgkm/L	2.0508	2.0388	2.0328	2.0412
Out Put					
Biodiesel/Batch	L	52	52	52	52
Glycerin/Batch	L	28	18.57	9.18	17.33
Washing of Biodiesel					
Prewashed Biodiesel	L	52	52	52	52
Electricity	KWh/L	0.07	0.07	0.07	0.07
Water/1L Biodiesel	L	0.5	0.5	0.5	0.5
Output					
Pure Biodiesel	L	50	50	50	50
Waste Water	L	0.54	0.54	0.54	0.54
Use of Biodiesel In engine					
Water washed Biodiesel/Batch	L	50	50	50	50
Transport	kgkm/Total Biodiesel Transported	88	88	88	88

The study examined three different scenarios for a multi-feedstock biodiesel plant, each with a different production yield. The yield percentages for type A, type B, type C and type

D were 85%, 65%, 70%, and 75%, respectively. The difference in yield can be attributed to the FFA (Free Fatty Acid) concentration of the various feedstock, which affects KOH consumption.

3.6.4 Impact Assessment

The impact assessment is carried out using the end Recipe 2016 endpoint[H] and midpoint[H], methods[124]. The Recipe 2016 is an update version of ReCiPe 2008 is used over the other characterization methods such as CML 2001 and Impact 2002+ due to the most recent indicators that cover most of the environmental impact categories[125]. ReCiPe mid point can assess 18 midpoint impact categories and merging them to form 3 endpoint categories. The midpoint indicators studied including Global warming(Kg CO_2 eq), stratospheric ozone depletion(Kg CFC eq), Ionizing radiations(KBq Co-60 eq), Fine particulate matter formation(kg PM2.5 eq), Terrestrial acidifications(Kg SO_2 eq), Fresh water eutrophication(Kg P eq), Marine eutrophication(Kg N eq), Terrestrial ecotoxicity(Kg 1,4-DCB), fresh water ecotoxicity(Kg 1,4-DCB), Marine ecotoxicity(Kg 1,4-DCB), Mineral Resource Scarcity(Kg Cu eq), Fossil resource scarcity(Kg oil eq), and water consumption(m^3).

3.6.4.a Global Warming Potential (GWP)

Global Warming Potential (GWP) measures the relative energy absorbed by the emissions of 1 ton of a specific greenhouse gas over a defined period, usually 100 years, in comparison to 1 ton of carbon dioxide (CO_2). It helps assess the contribution of different greenhouse gases to climate change[126][127]. The production of biodiesel contributes to GWP mainly through emissions linked to energy use during the cultivation of feedstocks, oil extraction, and the transesterification process (e.g., burning fossil fuels).

3.6.4.b Acidification Potential (AP)

Acidification potential measures the impact of pollutants like sulfur dioxide (SO_2) and nitrogen oxides (NOx) on ecosystem acidification. These substances react with atmospheric water to form acids such as sulfuric acid (H_2SO_4) and nitric acid (HNO_3), resulting in acid rain. This phenomenon negatively affects soil, aquatic ecosystems, and plants life[127], [128][129]. Biodiesel production can lead to acidification primarily through the emissions of nitrogen and sulfur compounds. These compounds stem from agricultural practices (e.g., fertilizer use), energy consumption (e.g., fossil fuels used for machinery), and the transportation of raw materials.

3.6.4.c Eutrophication Potential (EP)

Eutrophication potential describes the enrichment of water bodies with excessive nutrients, mainly nitrogen and phosphorus, resulting in the overgrowth of algae. This process depletes oxygen in aquatic ecosystems, disrupting biodiversity and harming aquatic life[130]. The eutrophication effect in biodiesel production is mainly attributed to the application of fertilizers during crop cultivation. The use of nitrogen and phosphorus in fertilizers contributes significantly to nutrient pollution in both land and water ecosystems. In comparison, waste oils generally have a much lower eutrophication impact as they bypass the need for crop cultivation[129].

3.6.4.d Ecotoxicity

Ecotoxicity refers to the potential harm that chemicals such as pesticides, herbicides, and heavy metals can cause to ecosystems, including plants, aquatic organisms, and soil fauna. This can lead to the loss of biodiversity and degradation of ecosystem functions[131]. The cultivation of biodiesel feedstocks, especially in intensive agricultural systems, can release harmful chemicals such as pesticides and fertilizers into the environment, contributing to ecotoxicity. These substances can negatively impact both terrestrial and aquatic ecosystems.

3.6.4.e Resource Depletion (Abiotic Depletion Potential - ADP)

Abiotic depletion refers to the depletion of non-renewable natural resources, including fossil fuels, minerals, and metals. Abiotic Depletion Potential (ADP) quantifies the environmental impact of consuming these resources throughout a product's life cycle [132]. Biodiesel production contributes to resource depletion, primarily due to fossil fuel consumption for energy in feedstock cultivation and the extraction of metals and minerals for manufacturing equipment.

3.6.4.f Water Use and Water Scarcity

Water use refers to the total amount of water consumed during the production process, while water scarcity indicates the impact on water resources in regions where freshwater availability is limited. This is particularly important in water-stressed areas[133], [134]. Biodiesel production can be water-intensive, especially during feedstock cultivation and the transesterification process.

3.7 Social Analysis

The social analysis of biodiesel production in this study aims to examine the knowledge, attitudes, behaviors, and perceptions of the key stakeholders towards the biodiesel industry. This analysis is essential for understanding the societal acceptance of biodiesel and investigative complications to its broader implementation. The stakeholders examined in this study include academic institutions, industry leaders, policy organizations, agricultural research institutes, hotels sector, and end users, such as farmers.

The research methodology was designed to explore the social dimensions of biodiesel production, focusing on both the potential advantages and concerns related to its adoption. This study employed a structured survey approach, with customized Google Forms distributed to each stakeholder group.

3.8 Methodology for Social Analysis

The methodology includes selection of different key stakeholders, survey design and data collection, and data analysis,

3.8.1 Selection of different key stakeholders

The study focused on gathering perspectives from various key stakeholders to understand their views on biodiesel production. Academia was surveyed to gauge awareness of biodiesel as an alternative fuel, its environmental benefits, and its significance in research across disciplines like environmental science, engineering, and agriculture. Industry stakeholders, including energy companies, manufacturers, and transport sectors, were asked about their knowledge of biodiesel and its potential integration into their operations. Policy institutes provided insights into their understanding of biodiesel's role in sustainable energy transitions and their stance on related government policies. Agricultural research institutes were questioned on their knowledge of biodiesel feedstocks, its role in sustainable farming, and their level of support for biodiesel research. Hotels and suppliers were surveyed regarding their waste oil disposal practices and willingness to contribute to biodiesel production. Lastly, farmers were asked about their familiarity with biodiesel, its use in farming equipment, and the perceived benefits it could offer in terms of cost and environmental impact.

3.8.2 Data collection and questionnaire design

Data collection for the study was conducted through surveys using the Knowledge, Attitude, and Practice (KAP) model[135], which included both closed-ended questions (Likert scale) for quantitative analysis and open-ended questions for qualitative insights. The questionnaire comprised both quantitative and qualitative questions to ensure a comprehensive social analysis. The quantitative questions were designed using a Likert scale, making them easy to understand while allowing for refined responses[136]. This approach facilitated the quantitative analysis of subjective opinions and attitudes, enhancing the robustness of the study. The questionnaires along with its responses are attached in Appendix II.

The surveys covered key aspects such as knowledge of biodiesel, its production processes, feedstocks, and environmental benefits; attitudes towards its potential as a renewable energy source and social acceptance; practices regarding the use of biodiesel or its by-products and willingness to adopt biodiesel production; perceptions of its social, environmental, and economic implications; and support for government policies, incentives, and regulatory frameworks. Customized Google Forms were distributed across various stakeholder groups, including academia (professors, researchers, and students), industry professionals (energy, manufacturing, and transportation sectors), policy institutes (government officials and policy analysts), agricultural research institutes, hotels and suppliers (local hotel chains), and farmers (end users).

3.8.3 Data Analysis

After completing data collection, both quantitative and qualitative analysis methods were employed to interpret the responses. The quantitative analysis involved descriptive statistics, such as frequency counts, averages, and distributions, to assess stakeholders' knowledge, support, and practices related to biodiesel. Meanwhile, the qualitative analysis focused on thematic coding of open-ended responses to uncover recurring patterns. The primary themes identified included challenges to biodiesel adoption, recommendations for enhancing its utilization, and societal concerns, offering valuable insights into stakeholders' perspectives on the social implications of biodiesel.

3.9 Machine learning

This study employs a machine learning approach utilizing a Artificial neural network (ANN) to estimate biodiesel yield, emissions, and production costs per liter based on key input factors related to five different biodiesel feedstocks. The model combines experimental data with predictive analytics to optimize production strategies and evaluate sustainability outcomes.

3.9.1 Data set

The dataset used for modeling was generated using MATLAB's design of experiments (DoE) methodology, which allowed for systematic data collection by setting specific parameter bounds. These bounds were determined based on real-time data monitoring from multiple sources over several operational cycles to ensure a comprehensive representation of the biodiesel production process. The dataset spans 100 days of observations and includes key input variables such as Free Fatty Acids (FFAs), feedstock cost, feedstock quantities, and the distance between collection points and the biorefinery. FFAs are a crucial factor in determining feedstock quality and production efficiency, while the cost and quantity of feedstocks influence the economic feasibility of biodiesel production. Additionally, the transportation distance impacts both logistics costs and associated carbon emissions.

The output variables in the dataset include biodiesel blend yield, fuel cost per liter, and emissions per kilogram of biodiesel produced. The biodiesel blend yield represents the efficiency of conversion from feedstock to biodiesel, while the fuel cost per liter reflects the overall production expenses, including raw material costs and processing charges. Emissions per kilogram of biodiesel produced provide insights into the environmental impact of the production process. The data on FFAs and biodiesel yield were obtained through controlled laboratory experiments using a 50L pilot-scale plant, ensuring reliability in the experimental results. Additionally, emissions data were derived through a life cycle assessment (LCA) using SimaPro software, enabling a detailed evaluation of the environmental footprint associated with biodiesel production from different feedstocks.

To build and validate the predictive model, the dataset was divided into three subsets: training, validation, and testing. The training set comprised 75% to 80% of the total data, providing the model with sufficient data to be trained. The validation and test sets accounted for 10% to 15% each, allowing for fine-tuning and performance evaluation. Multiple split ratios were tested to determine the optimal configuration for achieving precise and reliable results. This strategic partitioning ensured that the model was well-trained while minimizing the risks of overfitting or underfitting, ultimately improving its predictive accuracy and robustness.

3.9.2 Data Processing

The datasets were normalized using the min-max normalization method as shown in the equation below to facilitate convenience and efficiency in model training. The normalized dataset was subsequently employed for training, testing, and validation purposes.

$$X_{norm} = \frac{(X - X_{min})}{(X_{max} - X_{min})} \qquad \text{Equation 3.4}$$

The wights and the input parameters were calculated using the equations below,

$$W_{i,j} = \frac{Q_i}{\sum_{j=1}^{n} Q_{ij}} \qquad \text{Equation 3.5}$$

$$WQ_{i,j} = W_{i,j} \times Q_{i,j} \qquad \text{Equation 3.6}$$

$$WFFA_{i,j} = W_{i,j} \times FFA_{i,j} \qquad \text{Equation 3.7}$$

$$WC_{i,j} = Wi,j \times C_{i,j} \qquad \text{Equation 3.8}$$

$$WE_{i,j} = W_{i,j} \times E_{i,j} \qquad \text{Equation 3.9}$$

Fuel cost per liter is calculated as;

$$C_{i,combined} = \sum_{j=1}^{n} W_{i,j} \times C_{i,j} + \frac{\sum_{j=1}^{n} Wi,j \times Ti,j \times Di,j}{\sum_{j=1}^{n} Qi,j} + \text{Pi} \qquad \text{Equation 3.10}$$

Artificial Neural Networks (ANN) are among the most commonly used machine learning approaches. In this study, ANN was applied to predict biodiesel yield, emissions throughout the production process, and fuel cost per liter based on input features. The models were developed using MATLAB 2022b, utilizing the Neural Network (NN) toolbox for ANN modeling.

To achieve optimal results and minimize errors, multiple runs were conducted, adjusting the number of neurons in each layer and dividing the data into training, validation, and test sets. The mean square error (MSE) was calculated for each fold and averaged across all runs to assess model accuracy. This approach ensures a reliable evaluation of the model's performance while reducing the risk of overfitting or underfitting.

3.9.3 Development of Biodiesel yield equation

Based on the experimental data relation between the biodiesel yield and FFA was developed by using the Curve fitting tool box in the Matlab. The R square calculated for the curve fitting was 0.99522. Since biodiesel yield exhibits a linear dependency on FFA content as shown in the Figure 3.10 below.

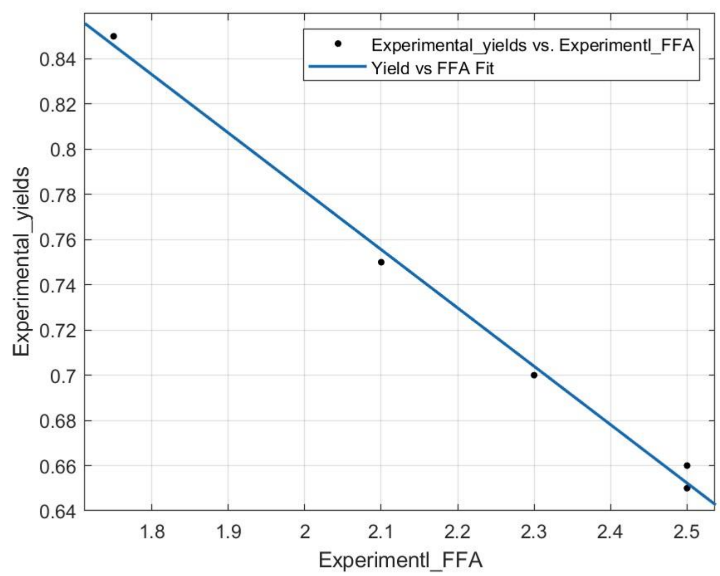


Figure 3.10 Regression of Yield Vs FFA

A regression equation was integrated into the model as shown below.

$$Y_{i,combined} = -0.2538 \times \sum_{j=1}^{n}(Wi,j \times FFAi,com) + 1.298 \qquad \text{Equation 3.11}$$

This equation provides correlation between FFA levels and biodiesel yield, where higher FFA content generally leads to lower biodiesel output. The daily weighted FFA content of te mixture were calculated using the equation below.

$$FFA_{i,combine} = \sum_{j=1}^{n} Wi,j \times FFAi,j \qquad \text{Equation 3.12}$$

3.9.4 Network

Machine learning (ML) modeling for biodiesel production was performed using an artificial neural network (ANN) with the Levenberg-Marquardt (LM) backpropagation algorithm. Among different ANN architectures, the backpropagation artificial neural network (BP-ANN) is the most commonly used due to its high efficiency. The Levenberg-Marquardt learning algorithm was selected for its effectiveness in optimizing network training, while the trainlm function was chosen for its faster convergence rate and lower computational time. This function helps minimize the number of training epochs required for network learning. Additionally, gradient descent with momentum weights was applied as the learning function to improve optimization.

The transfer function plays a crucial role in ANN development by converting input data into a suitable response for network processing. The trainlm function updates weights using Levenberg-Marquardt optimization, making it a preferred approach for precise modeling of experimental data. The feedforward BP-ANN used in this study integrates first-order gradient descent for training, leading to improved training speed and accuracy.

As shown in Figure 3.11 the architecture, the ANN model consists of five layers. The input layer includes 20 neurons, representing parameters such as feedstock quantity, distance to the biorefinery, free fatty acid (FFA) content, and feedstock cost. The first hidden layer comprises 8 neurons activated by the tansig transfer function, while the second hidden layer consists of 6 neurons using the logsig transfer function. The output layer provides predictions for biodiesel yield, emissions, and fuel cost per liter. Since ANN performance is highly dependent on the number of neurons in the hidden layers, an optimal configuration was carefully selected.

Tansig activation function

$$f(x) = \frac{2}{1+e^{-2x}} - 1 \qquad \text{Equation 3.13}$$

Logsig activation function

$$f(x) = \frac{1}{1+e^{-x}} \qquad \text{Equation 3.14}$$

The ANN modeling was performed using MATLAB. The input and output datasets were imported and normalized using a standard normalization equation. The ANN architecture was then defined by selecting the appropriate number of neurons, algorithm, and activation functions. Model performance was evaluated based on the correlation coefficient (R), with an R-value above 0.95 considered satisfactory. Finally, the trained ANN was used to generate predictions for biodiesel yield, emissions, and fuel cost per liter.

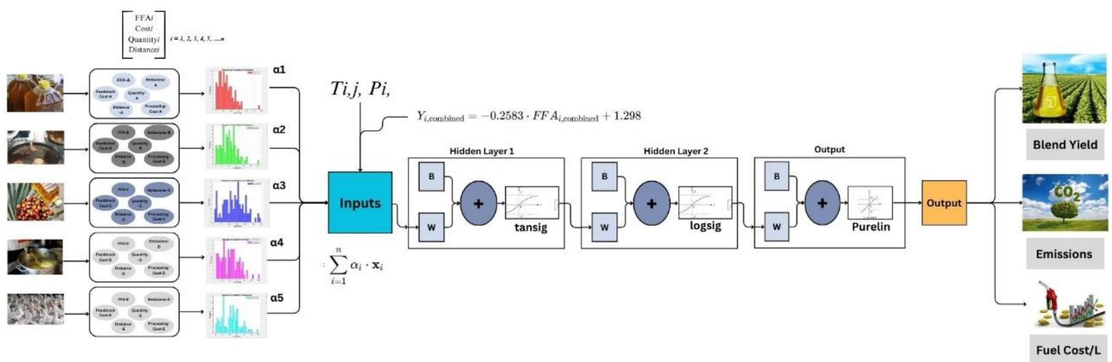


Figure 3.11 Architecture of Neural Network

3.9.5 Methodology

The Figure 3.12 illustrates the proposed methodology for developing a Feedforward Backpropagation Artificial Neural Network (FFBP ANN) to predict biodiesel cost per liter, emissions per liter over its life cycle, and blend yield. The process for selecting the most suitable FFBP ANN model and evaluating the impact of input parameter variations, such as feedstock availability, on model performance is outlined as follows.

A dataset consisting of 100 observations was collected, containing both input and target parameters. The input parameters included the Free Fatty Acid (FFA) content of each feedstock, the distance from collection points to the biorefinery, the availability of feedstocks, and their associated costs. The target parameters comprised the blend yield, emissions generated from the blended feedstock, and the cost per liter of the final biodiesel product.

The selection of input and output parameters was determined based on their significance, while the range for the number of neurons in the hidden layers was established through multiple experimental runs. Once the appropriate number of inputs, hidden, and output neurons was defined, the models were trained and simulated using MATLAB 2022b, specifically utilizing the Neural Network Toolkit.

After the training phase, several performance metrics were calculated to assess the effectiveness of each ANN model. The models were compared using key performance indicators, with the best model chosen based on the highest correlation coefficient (R) and the lowest mean squared error (MSE). Finally, actual and predicted values were plotted on a graph to visually evaluate the predictive accuracy of the ANN.

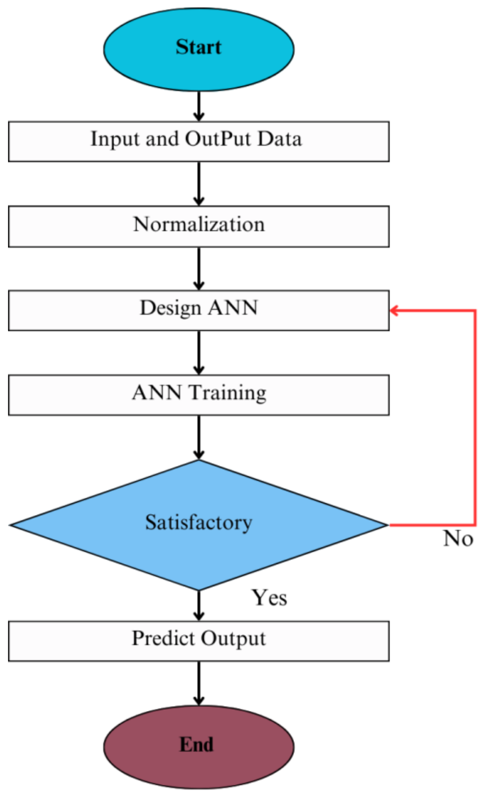


Figure 3.12 Process Flow chart

3.9.6 Evaluation indices

To assess the accuracy of the predictive model, evaluation metrics such as the coefficient of determination (R^2) and mean squared error (MSE) were used to compare experimental and predicted results. MSE, one of the most commonly used error metrics, was applied in this study to measure the difference between actual and predicted values.

$$\text{MSE} = MSE = \frac{1}{N}\sum_{i=1}^{N} (Y_{true,i} - Y_{Pred,i})^2 \qquad \text{Equation 3.15}$$

$$R^2 = 1 - \frac{\sum(Y_{exp} - Y_{Pred})^2}{\sum(Y_{exp} - Y_{mean\ exp.})^2} \qquad \text{Equation 3.16}$$

3.10 Summary

This chapter provides in details the experimental approach for biodiesel production, including feedstock selection, transesterification reaction. It outlines the characterization techniques used, such as FTIR and GC-MS, to analyze the chemical composition of biodiesel as well as its physiochemical properties. The methodology for the life cycle assessment presented, describing impact categories such as global warming potential and resource depletion. Social analysis methodologies, including stakeholder surveys, are explained. The final section provides the methodology used for Machine learning using artificial neural network (ANN) model used to predict biodiesel yield, emissions, and cost.

Chapter 4 Experimental Results and Analysis

This chapter presents the experimental results, including the yield of biodiesel, heating value, specific gravity, and flashpoint. Additionally, acid value analysis was conducted to correlate with the FFA value. Furthermore, this chapter includes FTIR and GC-MS analyses for the characterization of biodiesel.

4.1 Yield of Biodiesel

The yield of biodiesel is a critical parameter in assessing the efficiency and viability of different feedstocks for biofuel production. The biodiesel yields obtained from the experimental investigation of Type-A, Type-B, Type-C, and Type-D feedstocks are presented in Table 4.1.

The oil-to-methanol ratio and reaction temperature play a crucial role in the transesterification process, directly affecting biodiesel yield. Maintaining the optimal temperature is essential for maximizing production efficiency, with 60°C being the ideal temperature for this reaction[137]. Additionally, the oil's acid value has a significant impact on the yield.

Type-A feedstock achieved the highest biodiesel yield at 85%, demonstrating its strong potential for efficient biodiesel production. This high yield is likely due to its favorable fatty acid composition and lower impurity levels, which promote a more complete transesterification reaction. In comparison, Type-B feedstock produced the lowest yield at 65%, possibly due to its lower lipid content and the presence of complex compounds that interfere with biodiesel conversion. The reduced yield may also result from free fatty acids (FFAs), which can lead to soap formation during transesterification, thereby limiting biodiesel recovery. Type-C and Type-D feedstocks yielded 70% and 75%, respectively. While these feedstocks are viable for biodiesel production, further optimization of processing parameters, such as catalyst concentration and reaction temperature, may be required to improve their efficiency.

Table 4.1 Yield of different sourced oil

Type of Feedstock	Yield
Type-A Feedstock	85%

Type-B Feedstock	65%
Type-C Feedstock	70%
Type-D Feedstock	75%

4.2 Acid Value

The acid value and free fatty acid (FFA) content are critical parameters in determining the suitability of feedstocks for biodiesel production. These values influence the transesterification process and the final biodiesel yield. Table 4.2 summarizes the acid values and FFA contents for the feedstocks investigated.

Acid value (AV) analysis was performed to assess the free fatty acid (FFA) content in feedstocks, a key factor in determining their suitability for biodiesel production. Feedstocks with high AV require esterification pretreatment to lower FFA levels, which enhances biodiesel yield and minimizes soap formation during transesterification. Additionally, AV analysis ensures product quality and helps reduce environmental impact. The acid value of samples collected from various local hotels and restaurants was measured using the titration method. Results varied depending on how frequently the oil had been used for frying. Five samples were tested for each case, and the average values are reported. Repeated heating leads to the breakdown of fatty acid chains, increasing the acid value of the oil. Handling high-FFA oils and methanol requires precautions due to risks such as flammability, toxicity, and equipment corrosion. Essential safety measures include proper methanol storage, the use of corrosion-resistant materials, and emission control systems. Additionally, effective wastewater management and adherence to safety protocols are crucial for sustainable and secure biodiesel production.

Table 4.2 Acid Value FFA(%) value of different sourced oil

Type of Feedstock	**Acid Value(mgKOH/g)**	**FFA**
Type-A Feedstock	3.5 ± 0.05	1.75 ± 0.03
Type-B Feedstock	5.0 ± 0.10	2.5 ± 0.05
Type-C Feedstock	4.0 ± 0.07	2.0 ± 0.04
Type-D Feedstock	4.2 ± 0.08	2.1 ± 0.05

The lowest acid value was recorded for Type-A feedstock (3.5 ± 0.05 mg KOH/g), corresponding to an FFA content of 1.75 ± 0.03%. This relatively low FFA content suggests a cleaner feedstock with minimal impurities, leading to higher biodiesel yields. The lower acid value implies reduced risk of soap formation during the transesterification process, which aligns with the high biodiesel yield (85%) obtained from Type-A feedstock. Conversely, Type-B feedstock exhibited the highest acid value (5.0 ± 0.10 mg KOH/g) and FFA content (2.5 ± 0.05%) followed by Type C and D with FFA value of 2.0 and 2.1. The elevated acid value confirms the presence of more free fatty acids, which are known to cause complications in biodiesel production, including soap formation, lower biodiesel yield, and longer reaction times.

4.3 Heating Value

The experimental analysis examined the heating value of biodiesel derived from various sources and its blends with fossil diesel, comparing the results to conventional diesel. Table 4.3 presents the heating values of different biodiesel samples. The highest heating value was recorded for Type A biodiesel, produced from canola vegetable oil, while the lowest was observed for Type B biodiesel.

Table 4.3 Heating Value of Different Sourced Biodiesel

Type of Feedstock	**Heating Value (MJ/kg)**
Type-A Biodiesel	35.78 ± 0.20
Type-B Biodiesel	33.74 ± 0.25
Type-C Biodiesel	35.02 ± 0.15
Type-D Biodiesel	34.425 ± 0.30

The heating value of biodiesel is influenced by the presence of long-chain methyl esters. Since biodiesel contains these long chains, it has a relatively high calorific value. However, when compared to fossil diesel, its heating value remains lower[138]. A fuel with a lower calorific value will be consumed in greater quantities than a higher-calorific-value fuel to produce the same power. Biodiesel contains less carbon and hydrogen compared to fossil diesel, resulting in a lower heating value[139]. Fossil diesel has the highest heating value at 42.84 MJ/kg, while the lowest heating value was recorded for pure biodiesel (B100) at 35.8 MJ/kg. The figure below illustrates the heating values of various biodiesel blends. Experimental tests were conducted for each blend, and the values were documented in this study. Based on the experimental results, a proposed equation is presented.

$$\text{Heating value} = 0.0009x^2 - 0.1502x + 42.343 \qquad \text{Equation 4.1}$$

Where x represents the volume percentage of biodiesel in the blend.

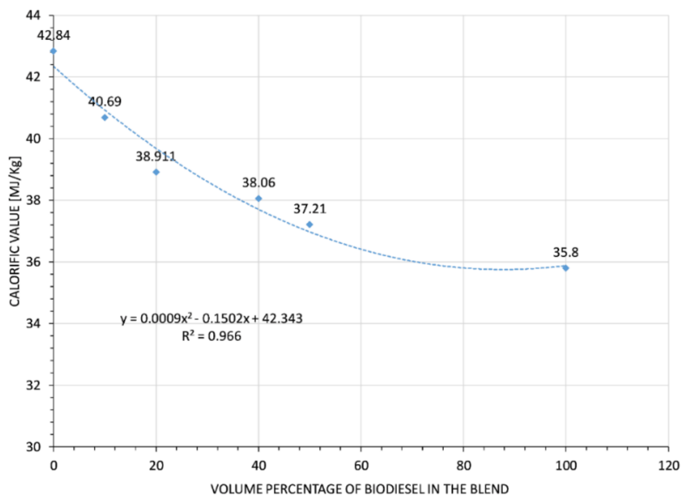


Figure 4.1 Heating Value of different Blends

From experiments as shown in Figure 4.1, it is observed that the heating value decreases with increase in proportion of biodiesel in each blend. Pure biodiesel has less heating value than fossil diesel and is approximately 16.4% less than the heating value of fossil diesel.

4.4 Flash Point

Flash point refers to the temperature at which the flame appears when it is subjected to fire. This property is particularly significant for ensuring safe storage and transportation of fuel. According to the ASTM D93 standard, the recommended flash point for biodiesel is 174°C, which was consistently achieved in all samples of biodiesel produced from waste cooking oil in this study.

It is noted that biodiesel has a considerably higher flash point compared to fossil diesel, which typically ranges between 55°C and 66°C. This higher flash point makes biodiesel more safer for handling, storage, and transportation as it reduces the risk of fire hazards. In contrast, fuels with lower flash points pose a greater risk of combustion and explosion, particularly under elevated temperature conditions. The superior flash point of biodiesel reinforces its potential as a safer and more secure alternative to traditional fossil fuels.

4.5 Specific Gravity

The specific gravity of biodiesel, also known as its density relative to water, plays a significant role in determining its combustion behavior, fuel injection efficiency, and storage stability. Various factors influence this property, including the choice of feedstock and the degree of purification during the production process. In this study, the specific gravity of 0.88 for biodiesel sample was assessed using a hydrometer.

The findings align closely with the ASTM standard, which specifies an acceptable specific gravity range for biodiesel between 0.75 and 0.90. The measured values suggest an optimal balance between density and fluidity, which is critical for proper atomization and combustion in diesel engines. A higher specific gravity can lead to inefficient combustion, while a lower value may negatively affect the fuel's lubricating properties. The uniformity of specific gravity measurements across various biodiesel samples highlights the efficiency of the production and purification processes in achieving consistent fuel quality.

4.6 3/27 test

The 3-27 test is carried out in order to make sure that the reaction with alcohol is completed and all the triglyceride in oil is converted to biodiesel. 3 ml of biodiesel is added to 27ml of methanol at room temperature with vigorous shake. The solution is left for 15mins and if anything settles down in the bottom or if any spot of oil appears in the bottom, it means that the reaction is not completed and still needs the transesterification to convert all the remaining triglycerides to biodiesel. It also means that the amount of catalysts used was not enough. If the spots of oil do not appear in the bottom, then it means that all the oil is converted to biodiesel. Here, all conversion process and 3/27 tests were successful.

4.7 FTIR

Fourier Transform Infrared (FTIR) spectroscopy is a commonly employed analytical method for characterizing the chemical structure and composition of biodiesel. This method is valuable for identifying the functional groups present in biodiesel and monitoring the transesterification process. By measuring the absorption of infrared radiation across a range of wavelengths, FTIR provides detailed information about molecular vibrations that correspond to specific chemical bonds.

4.7.1 FTIR of Feedstocks

Figure 4.2 shows the FTIR spectrum of oils collected from different sources as tabled earlier. Each peak in the in the spectrum represents each functional group. The peak at ~3748cm^{-1} represents the O-H group in all different types of oils. The peak at wave number ~3007.56cm^{-1} in type B, ~3007.13 cm^{-1} in type C, ~3007.24cm^{-1} in type D and ~3009.01 in type A represent the C-H functional group. The peak that is recorded around the ~2922 cm^{-1} and 2853 cm^{-1} in all types of oil represent the asymmetrical and symmetrical C-H stretching of CH_2 group[140]. The peaks at wave numbers ~1743.89 cm^{-1}, 1744.04 cm^{-1}, 1743.92 cm^{-1} and 1743.44cm^{-1} represent the carbonyl(C=O) group stretching vibration in ester group. The peaks observed around ~1377cm-1 and ~1237.63 corresponds to C-H bending. The peak observed on the wave number ~1098.4 cm^{-1} in type C oil is possible due to the presence of ketones in the palm oil while this peak is not observed in other sources as type C oil is used palm oil.

The band at ~1160cm^{-1} and ~1119cm^{-1} in all different oils represent the C-O-C group in ester. In addition to this, the peaks observed at ~1000cm^{-1} may be due to the C-H out of plane deformation of the isolated trans-double bond or due to unsaturated fatty acids. The intensity of peaks is different at different locations as shown in the , which represent the amount of that functional group present in each type of oil. The intensity of ~1710 cm^{-1} in the type B oil is more comparison to all other types of oil which shows the less amount of ester functional group in comparison to all other types which is directly linked with the yield of biodiesel. The type B is used for frying the meat for the local cuisines in Country (Pakistan) and due to its multiple time usage the acid amount of free fatty acids is more than that of the other. The higher values of FFA and corresponding to lesser yield of biodiesel. The other reason which can be discussed that the type B is not pure oil it is mixed with vegetable fats as well as animal fats, which has affect the free fatty acids value of the feedstock.

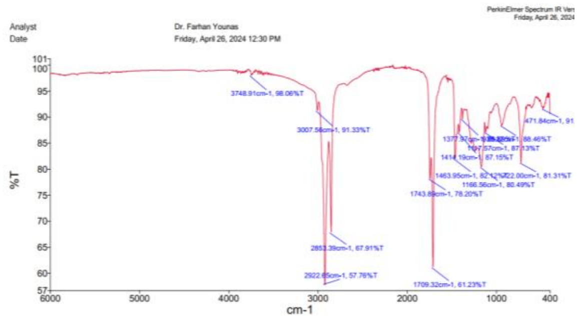


Figure 4.2 Type B feedstock

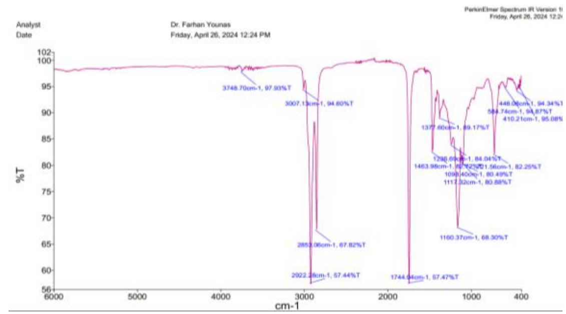


Figure 4.3 Type C Feedstock

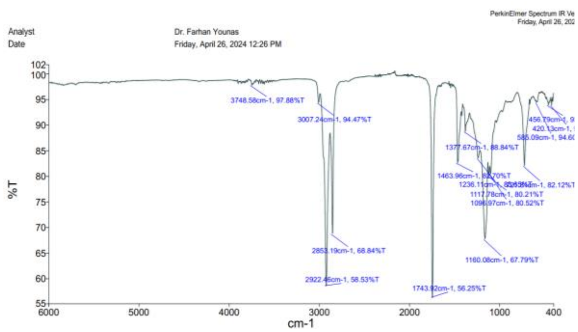


Figure 4.4 Type D Feedstock

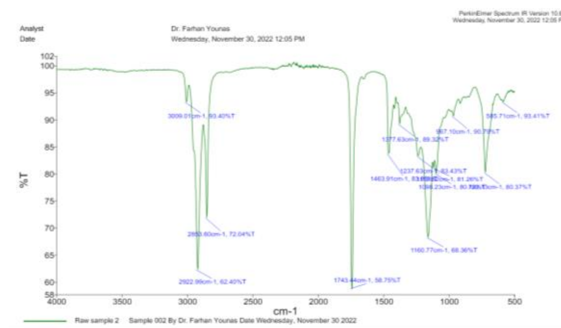


Figure 4.5 Type A Feedstock

4.7.2 FTIR of Biodiesel

The Figure *4.6* below shows the FTIR spectra of Biodiesel extracted from different sources of oil using the transesterification process. Each spectra represents the functional group intensity in each types of Biodiesel. The peaks at ~2922cm^{-1} and ~2853.3cm^{-1} represent the symmetric and anti-symmetric stretching vibration of C-H and C-H in CH_3 group. The strongest peak ~1743 cm^{-1} is due to the presence of C=O stretching vibration of carbonyl group in esters group. The peaks between ~1600cm^{-1} and ~1400cm^{-1} region shows the bending vibration of CH_2 and CH_3 aliphatic group[141].

The intensity of the peaks shows variation after the completion of the transesterification reaction. The plots at 1363cm^{-1},1377cm^{-1}, 1436cm^{-1}, and 1198cm^{-1} show a clear variation which represents formation of Fatty acid methyl ester (FAME) which is also called biodiesel. The peaks and 1363cm^{-1}, 1436cm^{-1}, and 1198cm^{-1} are increased as the FAME are produced and 1377cm^{-1} is decreased. If we observe comparatively in the spectra of biodiesel and its feed stocks the spectra at 1377cm^{-1} is disappeared from the biodiesel spectra as the reaction is completed which represents the conversion of the oil to biodiesel. This is the indicator that the chemical reaction is satisfactory and comparison drawn here are useful. The peak at 1198cm^{-1} in all the graphs of biodiesel provided the strongest signal change with the greater intensity as the transesterification is carried out. The change in the intensity at 1198cm^{-1} is due to the addition of the base catalyst. Figure 4.11 shows the comparison of the spectra of the biodiesel with the feedstock and clear variation can be recorded in the spectra which indicates the transition of the triglycerides to FAME formation. This is indicated by the disappearance of peaks observed at 1363cm^{-1}, 1377cm^{-1}, 1436cm^{-1} and 1198cm^{-1}.

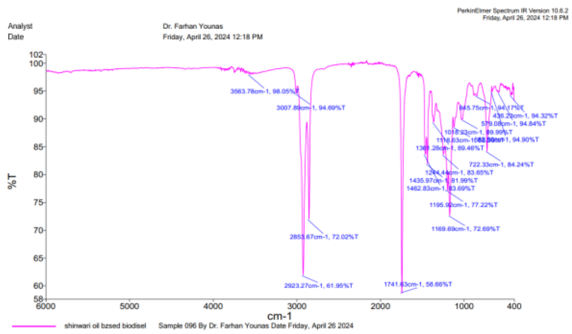


Figure 4.6 Type B Biodiesel

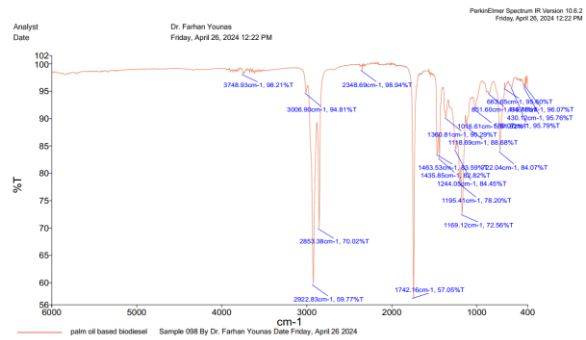


Figure 4.7 Type C Biodiesel

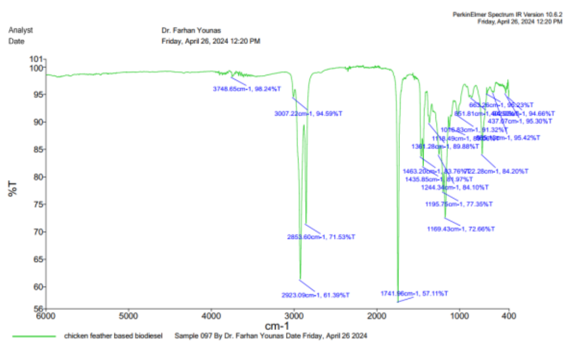


Figure 4.8 Type D Biodiesel

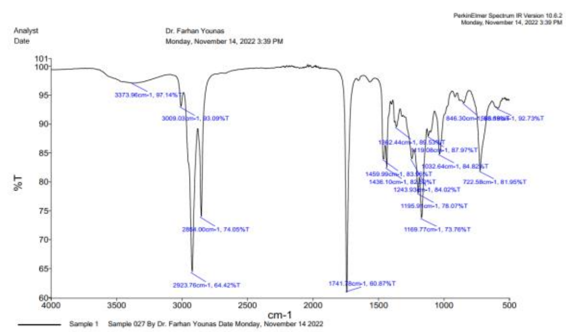


Figure 4.9 Type A Biodiesel

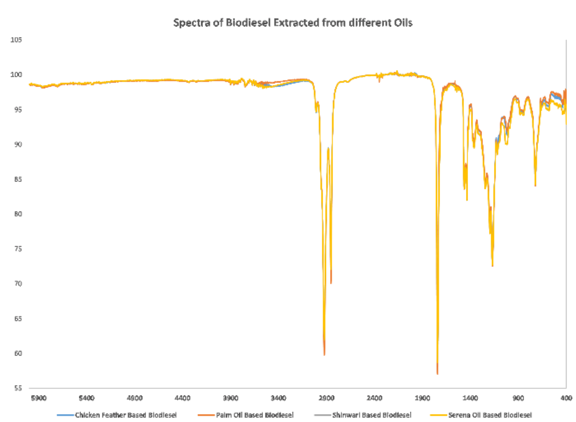


Figure 4.10 Spectra of Biodiesel extracted from different oils

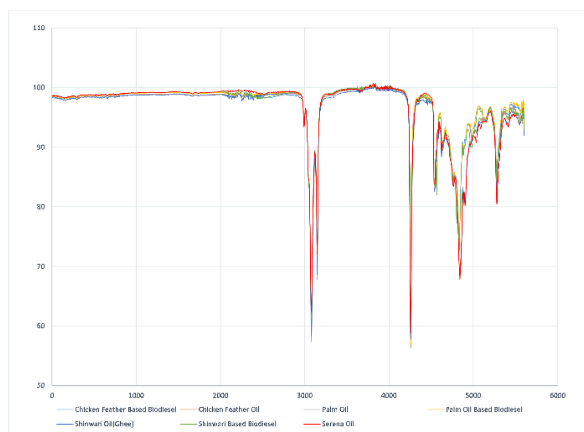


Figure 4.11 Comparison of Biodiesel spectra with feedstock

4.8 GCMS of Biodiesel

The chemical composition of biodiesel derived from various feedstocks was analyzed using gas chromatography-mass spectrometry (GC-MS) as shown in Figure 4.12

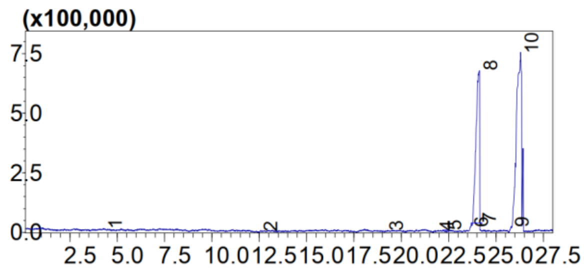


Figure 4.12 GCMS of Type A Biodiesel

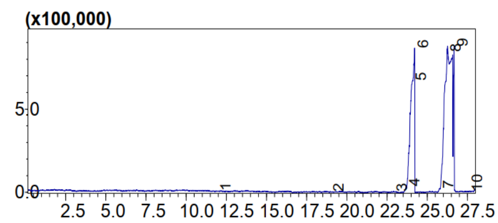


Figure 4.13 GCMS of Type B Biodiesel

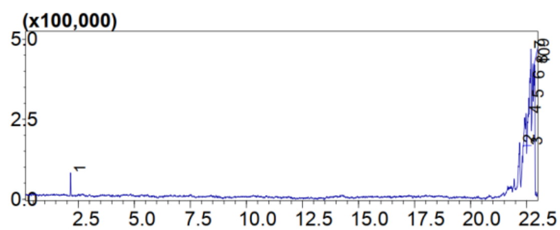


Figure 4.14 GCMS of Type C Biodiesel

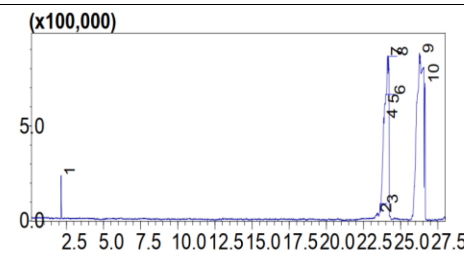


Figure 4.15 GCMS of Type D Biodiesel

The GC-MS results revealed distinct profiles for each biodiesel type, highlighting significant variations in their fatty acid methyl esters (FAMEs). Key components identified, as summarized in Table Below, include Hexadecanoic acid (C16:0), Octadecenoic acid (C18:1), and Eicosadienoic acid (C18:2), which play crucial roles in influencing biodiesel properties such as oxidative stability, cold flow behavior, and combustion performance.

Table 4.4 GCMS of Biodiesel from Various feedstocks

Peak. No	Type-D Biodiesel			Type-A Biodiesel			Type-B Biodiesel			Type-C Biodiesel		
	R. Time	Area (%)	Compound Name	R. Time	Area (%)	Compound Name	R. Time	Area (%)	Compound Name	R. Time	Area (%)	Compound Name
1	2.15	1.3	Trichloromethane	4.31	0.07	-	11.928	0.07	-	2.159	1.27	Trichloromethane
2	23.452	0.18	7-Hexadecenoic acid, methyl ester, (Z)	12.52	0.01	-	18.96	0.08	-	22.187	3.77	6-Octadecenoic acid, methyl ester, (Z)-

3	23.616	0.55	9-Octadecenoic acid (Z)-, methyl ester	19.157	0.05	-	22.895	0.08	-	22.34	12.73	6-Octadecenoic acid, methyl ester, (Z)-
4	23.855	15.65	13-Docosenoic acid, methyl ester, (Z)-	21.804	0.02	-	23.68	0.38	Decanoic acid, methyl ester	22.473	6.37	6-Octadecenoic acid, methyl ester, (Z)-
5	23.94	11.26	Cyclopropaneoctanoic acid, 2-octyl-, me	22.194	0.07	-	24.08	19.61	Hexadecanoic acid, methyl ester	22.594	14.88	6-Octadecenoic acid, methyl ester, (Z)-
6	24	10.83	Hexadecanoic acid, methyl ester	23.64	0.2	Nitric Acid, nonyl ester	24.212	11.48	Hexadecanoic acid, methyl ester	22.635	14.87	6-Octadecenoic acid, methyl ester, (Z)-
7	24.129	21.63	Hexadecanoic acid, methyl ester	23.701	0.32	Tetradecanoic acid, 12-methyl-, methyl ester	25.775	0.28	8,11-Eicosadienoic acid, methyl ester	22.69	9.24	6-Octadecenoic acid, methyl ester, (Z)-
8	24.184	12.97	Hexadecanoic acid, methyl ester	24.132	41.51	Hexadecanoic acid, methyl ester	26.241	36.75	Cyclopropane octanoic acid, 2-[(2-penty	22.774	18.57	6-Octadecenoic acid, methyl ester, (E)-
9	26.274	16.07	6-Octadecenoic acid, methyl ester, (Z)-	25.79	0.22	6-Octadecenoic acid, methyl ester, (Z)-	26.668	31.18	Heptadecanoic acid, 16-methyl-, methyl ester	22.829	11.07	6-Octadecenoic acid, methyl ester, (E)-
10	26.65	9.56	Methyl stearate	26.306	57.51	9-Octadecenoic acid, methyl ester, (E)-	25.57	0.09		22.86	7.24	6-Octadecenoic acid, methyl ester, (E)-

The chromatograms of the biodiesel samples, shown in the figure above, reveal that Type A had the highest concentration of C16:0 (Hexadecanoic acid, methyl ester) at 41.51% and a significant amount of C18:1 (9-Octadecenoic acid, methyl ester) at 57.51%. This composition aligns with the strong peak observed at a wave number of 1743 cm^{-1} in the FTIR analysis. This high saturation is linked to improved higher energy content(shown in figure), oxidative stability, better ignition quality, and reduced cold flow performance. Type B showed a blend of saturated and unsaturated FAMEs, with notable quantities of C16:0 (Hexadecanoic acid, methyl ester) at 19.61%, C18:1 (9-Octadecenoic acid, methyl ester) at 18.57%. This composition suggests the use of a feedstock mixture of fats and oils can be linked to lesser conversion efficiency in terms of heating value recorded. Type C was predominantly composed of unsaturated FAMEs, including C18:1 (6-Octadecenoic acid, methyl ester) at 31.18% and C18:2 (9-Octadecenoic acid, methyl ester) at 18.57%, with a moderate proportion of C16:0 (Hexadecanoic acid, methyl ester) at 14.87% confirmed by the strong observation of carbonyl group of ester in the FTIR. Type D exhibited a significant concentration of C16:0 (Hexadecanoic acid, methyl ester) at 21.63% and a notable amount of C22:1 (13-Docosenoic acid, methyl ester) at 15.65%, along with a smaller proportion of C18:1 (9-Octadecenoic acid, methyl ester) at 0.55%. This profile indicates a moderate balance between saturated and unsaturated FAME which has less intensity of ester functional group in the FTIR.

4.8.1 Comparison of FTIR with GCMS Results

The variation in the intensity of FTIR peak observed around 1743 cm^{-1} provides strong evidence of variation in the FAME composition for the presence of fatty acid methyl esters (FAMEs) identified in the GC-MS analysis, such as Hexadecanoic acid, methyl ester, and Methyl stearate. Furthermore, the change in peak intensity near 1198 cm^{-1} and disappearance of peak at 1377cm^{-1}, associated with the base-catalyzed transesterification process, aligns with the FAME profiles detected in GC-MS.

FTIR analysis provides robust qualitative evidence for the formation of esters, which is quantitatively supported by GC-MS data. However, the results suggest that GC-MS offers limited additional insights beyond the detailed composition already indicated by FTIR. This highlights FTIR as an effective and efficient standalone method for verifying FAME production in biodiesel synthesis.

4.9 Summary

This chapter outlines the experimental findings, including biodiesel yield, acid value analysis, lower heating value, flash point, and specific gravity. FTIR confirms the successful transesterification, while GCMS analysis provide the insight about the chemical composition of the biodiesel produced from each feedstock showing distinct chemical composition. A comparative analysis of different feedstocks highlights variations in yield and fuel quality. The results demonstrate the feasibility of using waste cooking oil and other feedstocks for biodiesel production while ensure fuel quality within standard limits.

Chapter 5 Life Cycle Assessment Results and Social Analysis

This chapter presents a sustainability assessment of biodiesel derived from various feedstocks by conducting an environmental life cycle assessment, alongside a social analysis to evaluate its societal impact.

5.1 Environmental Impact Assessment

The environmental impact of biodiesel production was assessed using the ReCiPe Midpoint and end point 2016 methodology, which evaluates various categories of environmental impacts. Five different scenarios were analyzed based on the feedstock types used: Type-A, Type-B, Type-C, and Type-D feedstocks, alongside fossil diesel for comparison.

5.1.1 ReCiPe 2016 Midpoint Results

The scenarios investigated included biodiesel made from type D Oil (Scenario 1), Type C Oil (Scenario 2), Type A Oil (Scenario 3), fossil diesel (Scenario 4), and Type B Oil (Scenario 5) as shown in Table 5.1 below. The feedstock used in biodiesel manufacturing is a critical aspect in determining its environmental impact. Specifically, the raw materials Free Fatty Acid (FFA) value has a direct impact on chemical use and biodiesel production. Higher FFA levels result in greater chemical use and lower biodiesel yields, shifting the contribution of biodiesel production to other impact categories.

Table 5.1 ReCiPE Mid-Point Results

Impact category	**Unit**	**Scenario-1 (Type-D Feedstock)**	**Scenario-2 (Type-C Feedstock)**	**Scenario-3 (Type-A Feedstock)**	**Scenario-4 (Fossil Diesel)**	**Scenario-5 (Type-B Feedstock)**
Global warming	kg CO2 eq	82.50325	85.30715	70.04687	232.8428	84.80749
Stratospheric ozone depletion	kg CFC11 eq	1.4E-05	1.47E-05	9.75E-06	2.41E-05	1.43E-05
Ionizing radiation	kBq Co-60 eq	2.68904	2.828971	1.790055	0.799215	2.939653
Fine particulate matter formation	kg PM2.5 eq	0.06485	0.068817	0.043918	0.124678	0.067738
Terrestrial acidification	kg SO2 eq	0.128448	0.136384	0.087457	0.353908	0.131233
Freshwater eutrophication	kg P eq	0.014235	0.015066	0.009486	0.005753	0.014653
Marine eutrophication	kg N eq	0.00103	0.00109	0.000681	0.00784	0.001041
Terrestrial ecotoxicity	kg 1,4-DCB	137.8648	145.4525	91.3463	219.833	137.0969
Freshwater ecotoxicity	kg 1,4-DCB	1.943712	2.049212	1.284547	0.908828	1.976577
Marine ecotoxicity	kg 1,4-DCB	2.549328	2.68811	1.684567	1.515476	2.581834
Mineral resource scarcity	kg Cu eq	0.120248	0.127467	0.085523	0.171401	0.122786

Fossil resource scarcity	kg oil eq	22.85816	24.36945	18.71555	127.339	25.05414
Water consumption	m3	0.331251	0.348098	0.255524	0.251698	0.357231

The SimaPro results shown in the Figure 5.1 below for biodiesel production from type A, B, C, and D oil show considerable differences in environmental impacts across multiple categories. Notably, type A emerges as a feasible feedstock option due to its smaller overall environmental footprint than type B, C and D.

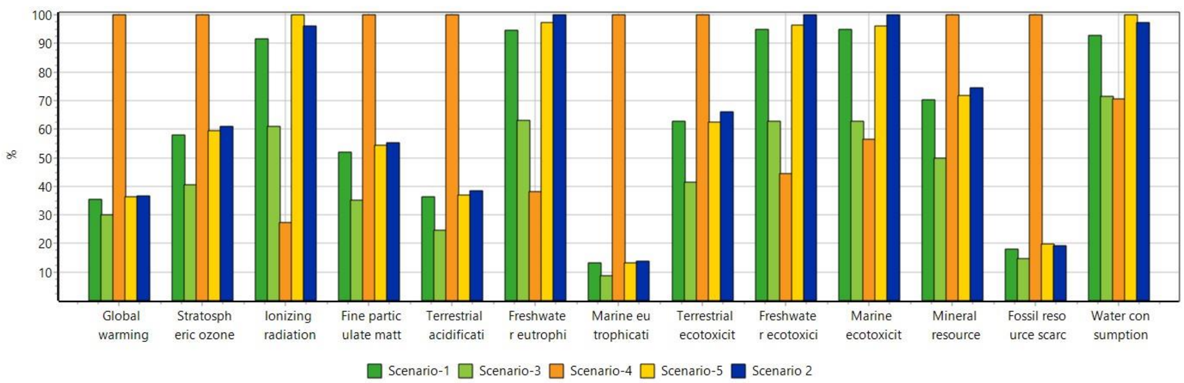


Figure 5.1 Environmental Impact of Biodiesel Produced from different feedstock and its comparison with fossil diesel

5.1.1.a Global Warming Potential (kg CO_2 eq)

The Life Cycle Assessment (LCA) results reveal that fossil diesel (Scenario-4) has the highest global warming potential (GWP) at 232.84 kg CO_2 eq, significantly surpassing all bio-based feedstocks. Among the bio-based alternatives, Type-A feedstock (Scenario-3) has the lowest GWP at 70.04 kg CO_2 eq, making it the most sustainable option. Type-D (Scenario-1), Type-B (Scenario-5), and Type-C (Scenario-2) have relatively similar GWP values ranging from 82.50 to 85.30 kg CO_2 eq, indicating that while they perform better than fossil diesel, they still contribute notable emissions. The lower GWP of bio-based feedstocks highlights their potential for reducing carbon emissions while strategies such as improved agricultural efficiency, renewable energy integration, and waste reduction can further enhance their climate benefits.

5.1.1.b Stratospheric Ozone Depletion (kg CFC11 eq)

Fossil diesel presents the highest ozone depletion potential at 2.41E-05 kg CFC11 eq, while Type-A feedstock has the lowest at 9.75E-06 kg CFC11 eq. This suggests that fossil diesel has a greater contribution to ozone depletion, likely due to emissions of ozone-depleting substances during fuel extraction, refining, and transportation. The variation among bio-based feedstocks is relatively small, with impacts ranging from 9.75E-06 to 1.47E-05 kg CFC11 eq, indicating that some feedstocks may still contribute to ozone depletion due to emissions from fertilizer and pesticide use. This highlights the need for sustainable farming practices and reduced reliance on ozone-depleting chemicals in biofuel production.

5.1.1.c Ionizing Radiation (kBq Co-60 eq)

Fossil diesel has the lowest ionizing radiation impact at 0.799 kBq Co-60 eq, whereas bio-based feedstocks show higher values, with Type-D feedstock at 2.689 kBq Co-60 eq and Type-B at 2.939 kBq Co-60 eq. This suggests that biodiesel production processes may involve more energy-intensive steps, potentially including electricity generation from nonrenewable sources. While fossil diesel has lower ionizing radiation emissions, this does not necessarily indicate overall environmental superiority, as its high GWP and resource depletion impacts outweigh this advantage.

5.1.1.d Fine Particulate Matter Formation (kg PM2.5 eq)

Fossil diesel exhibits the highest particulate matter emissions at 0.124 kg PM2.5 eq, whereas Type-A feedstock has the lowest at 0.043 kg PM2.5 eq. The significant contribution of fossil diesel to particulate pollution can be attributed to combustion-related emissions, which are known to cause respiratory issues and environmental degradation. Among the bio-based feedstocks, Type-D and Type-B have slightly higher particulate matter emissions compared to Type-A, suggesting that certain agricultural or processing methods may contribute more to air pollution. The lower particulate emissions of biofuels reinforce their potential benefits for improving air quality, particularly in urban areas.

5.1.1.e Terrestrial Acidification (kg SO_2 eq)

Fossil diesel has the highest acidification potential at 0.353 kg SO_2 eq, while Type-A feedstock has the lowest at 0.087 kg SO_2 eq. The high acidification impact of fossil diesel is primarily due to sulfur oxide (SO_2) and nitrogen oxide (NOx) emissions from combustion. Among bio-based feedstocks, Type-D and Type-B show slightly higher acidification impacts than Type-A, which could be linked to fertilizer use in feedstock cultivation. Reducing fertilizer application and optimizing combustion efficiency could further improve the acidification profile of biofuels.

5.1.1.f Freshwater Eutrophication (kg P eq)

Type-C feedstock has the highest freshwater eutrophication potential at 0.0150 kg P eq, while fossil diesel has the lowest at 0.0057 kg P eq. This indicates that agricultural runoff associated with bio-based feedstocks contributes significantly to phosphorus pollution in freshwater bodies. The higher eutrophication impact is likely linked to fertilizer application and wastewater discharges from processing facilities. Sustainable agricultural practices, such as precision fertilization and improved wastewater management, could help mitigate these negative effects.

5.1.1.g Marine Eutrophication (kg N eq)

Fossil diesel shows the highest marine eutrophication impact at 0.00784 kg N eq, while Type-A feedstock has the lowest at 0.000681 kg N eq. Fossil diesel combustion releases nitrogen oxides (NOx), which contribute to marine nutrient pollution, leading to harmful algal blooms and oceanic dead zones. Among the bio-based feedstocks, differences in marine eutrophication impacts suggest variations in nitrogen-related emissions, likely from agricultural runoff. Improved feedstock management strategies, such as controlled nitrogen application, could help reduce these impacts.

5.1.1.h Terrestrial Ecotoxicity (kg 1,4-DCB eq)

Fossil diesel has the highest terrestrial ecotoxicity impact at 219.83 kg 1,4-DCB eq, while Type-A feedstock has the lowest at 91.34 kg 1,4-DCB eq. The high ecotoxicity potential of fossil diesel is primarily due to emissions from fuel extraction, refining, and combustion. While bio-based feedstocks generally perform better, some variation exists, likely due to pesticide and herbicide use in agriculture. Transitioning to organic or low-chemical farming methods could further improve the ecotoxicity profile of biofuels.

5.1.1.i Freshwater and Marine Ecotoxicity (kg 1,4-DCB eq)

Fossil diesel shows the highest freshwater ecotoxicity impact at 0.9088 kg 1,4-DCB eq and marine ecotoxicity at 1.5154 kg 1,4-DCB eq, while Type-A feedstock has the lowest values at 1.28 kg 1,4-DCB eq (freshwater) and 1.68 kg 1,4-DCB eq (marine). Although biofuels generally have lower toxicity impacts, differences in ecotoxicity suggest that chemical inputs in agriculture and wastewater discharges from biofuel processing contribute to pollution. Sustainable farming techniques and improved water treatment can further minimize these effects.

5.1.1.j Mineral Resource Scarcity (kg Cu eq)

Fossil diesel has the highest mineral resource scarcity impact at 0.171 kg Cu eq, while Type-A feedstock has the lowest at 0.085 kg Cu eq. This indicates that bio-based feedstocks require fewer mined inputs, making them a more sustainable option. However, variations among biofuels suggest that some may require more resource-intensive processing, which could be addressed by using more efficient extraction and refining methods.

5.1.1.k Fossil Resource Scarcity (kg oil eq)

Fossil diesel exhibits the highest fossil resource scarcity impact at 127.34 kg oil eq, while Type-A feedstock has the lowest at 18.71 kg oil eq. This highlights the significant benefit of shifting to renewable feedstocks to reduce dependence on fossil fuels. Among bio-based feedstocks, minor variations exist, but all perform substantially better than fossil diesel in this category.

5.1.1.l Water Consumption (m^3)

Type-B feedstock has the highest water consumption at 0.357 m^3, while Type-A feedstock has the lowest at 0.255 m^3. This indicates that certain bio-based feedstocks require more irrigation or processing water, making water management a key consideration in large-scale biofuel adoption. While fossil diesel has slightly lower water consumption, its higher impacts in other categories outweigh this advantage. Efficient irrigation techniques and closed-loop water systems in biofuel processing could help reduce water demand.

5.1.2 Recipe End Point Results

End point assessment analysis was used to evaluate the end point results and its comparison. In the end point method all the damages are defined into three major categories which comprises of Human health, ecosystems, and resources. Eco system quality in the end point analysis is referred to impact contributed on terrestrial acidification, ecotoxicity(terrestrial, fresh water and marine), eutrophication, and land use. This category asses the overall impact of biodiesel production on the ecosystem quality. Human health refers to human carcinogenic toxicity, ozone formation, and particulate matter formation. This category is associated with impact caused by the environmental degradation, which involves number of diseases caused by certain activities and loss of life years. While the resources category is closely related to depletion rate of natural resources and energy sources.

The obtained results from the end point analysis is defined in percentage and categorized under three main damage categories. Referring to the results shown in the Figure 5.2 below fossil diesel has highest impact from the rest of all. The analysis indicates that the extraction of fossil diesel and its refinement needs a lot of resources such as fuel. The utilization of many process in the extraction of the fossil diesel such as drilling, distillation etc. require, massive amount of electricity and energy consumption which attributed to the overall impact of fossil diesel. If we compare the rest of the four scenarios, the waste cooking oil has less impact among the all cases. One of the reason for this can be the low FFA value of the waste cooking oil and it can results in the less transportation use and the use of the resources like electricity during the process. Hence it is concluded that the contribution of damage on the ecosystem, human health and resources is less in case of the waste cooking oil is used as feedstock for the biodiesel production process.

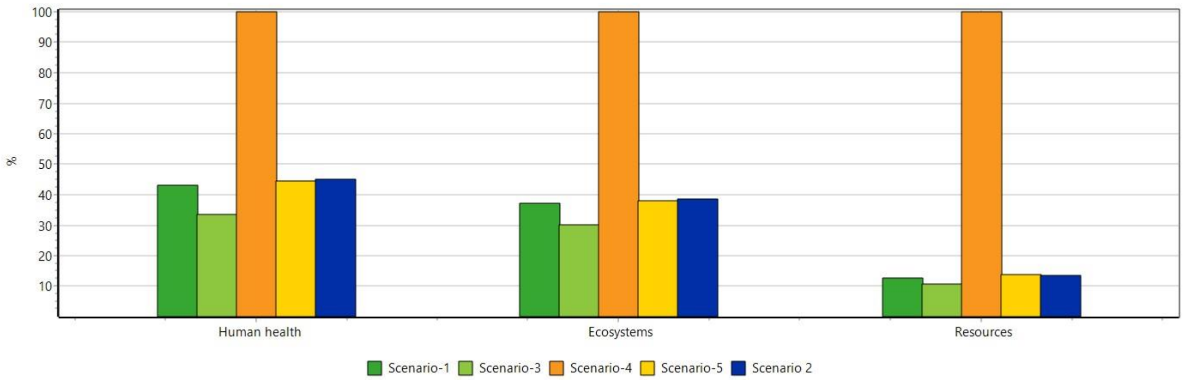


Figure 5.2 Damage Assessment of Biodiesel lifecycle for different categories

5.2 Social Analysis Results

This study gathered insights from various stakeholder categories to understand their concerns and perspectives regarding biodiesel. The respondents included professors and researchers from academia, scientists and researchers from agricultural research institutions, managers from hotel chains, policy analysts, and industry sector managers. Their perspectives provide valuable insights into the challenges and opportunities associated with biodiesel adoption.

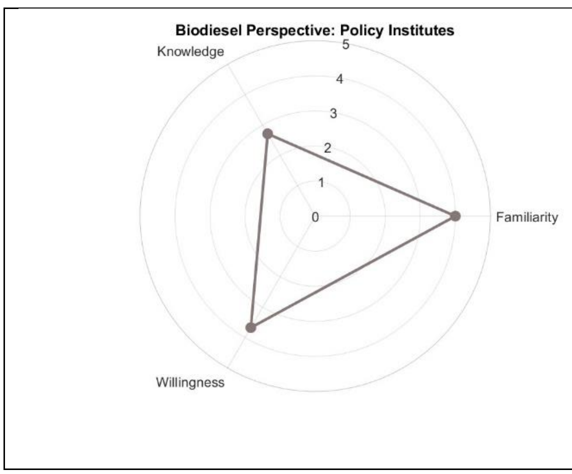
The hotels and restaurants sector, particularly hotel managers, highlighted that used cooking oil is primarily either disposed of or supplied to the soap-making industry. This indicates a lack of awareness or engagement in biodiesel production initiatives, suggesting an opportunity for better waste management strategies and biodiesel awareness programs within the sector.

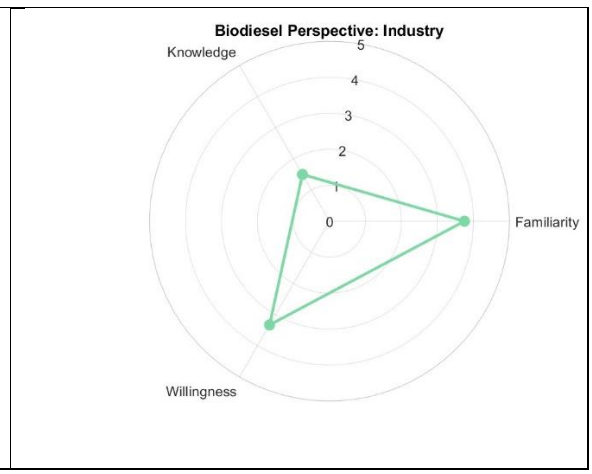
5.2.1 Analysis of Stakeholder Perspectives on Biodiesel

The Analysis on the perspective about biodiesel integration to industry and different sectors is shown in Figures below. Research institutes showed a high level of familiarity with biodiesel (81.25%) but had limited awareness of its benefits (27.59%), highlighting the need for stronger advocacy. Academia had the highest familiarity (93.75%) and full awareness of biodiesel benefits (100%), yet no general awareness (0.0%), suggesting minimal active involvement in biodiesel promotion. The hotel sector demonstrated the lowest awareness overall (25.0%) and no knowledge of biodiesel benefits, underscoring the necessity for targeted education on its role in waste management.

Companies exhibited moderate familiarity (67.86%) and a solid understanding of biodiesel benefits (71.43%), but no general awareness (0.0%), indicating that while they recognize its advantages, they may not actively pursue its adoption. Policy institutions had relatively high familiarity (75.0%) and full awareness of benefits (100%), but low general awareness (33.33%), pointing to a need for a deeper understanding of biodiesel applications to inform more effective policy decisions.

To improve biodiesel awareness and encourage adoption, tailored educational programs should be developed for different stakeholders. Bridging the gap between awareness and action will require incentives and collaborative initiatives. Strengthening partnerships between industry, government, and academia can help turn knowledge into practice, while improved communication through social media, industry conferences, and workshops can effectively promote biodiesel use.





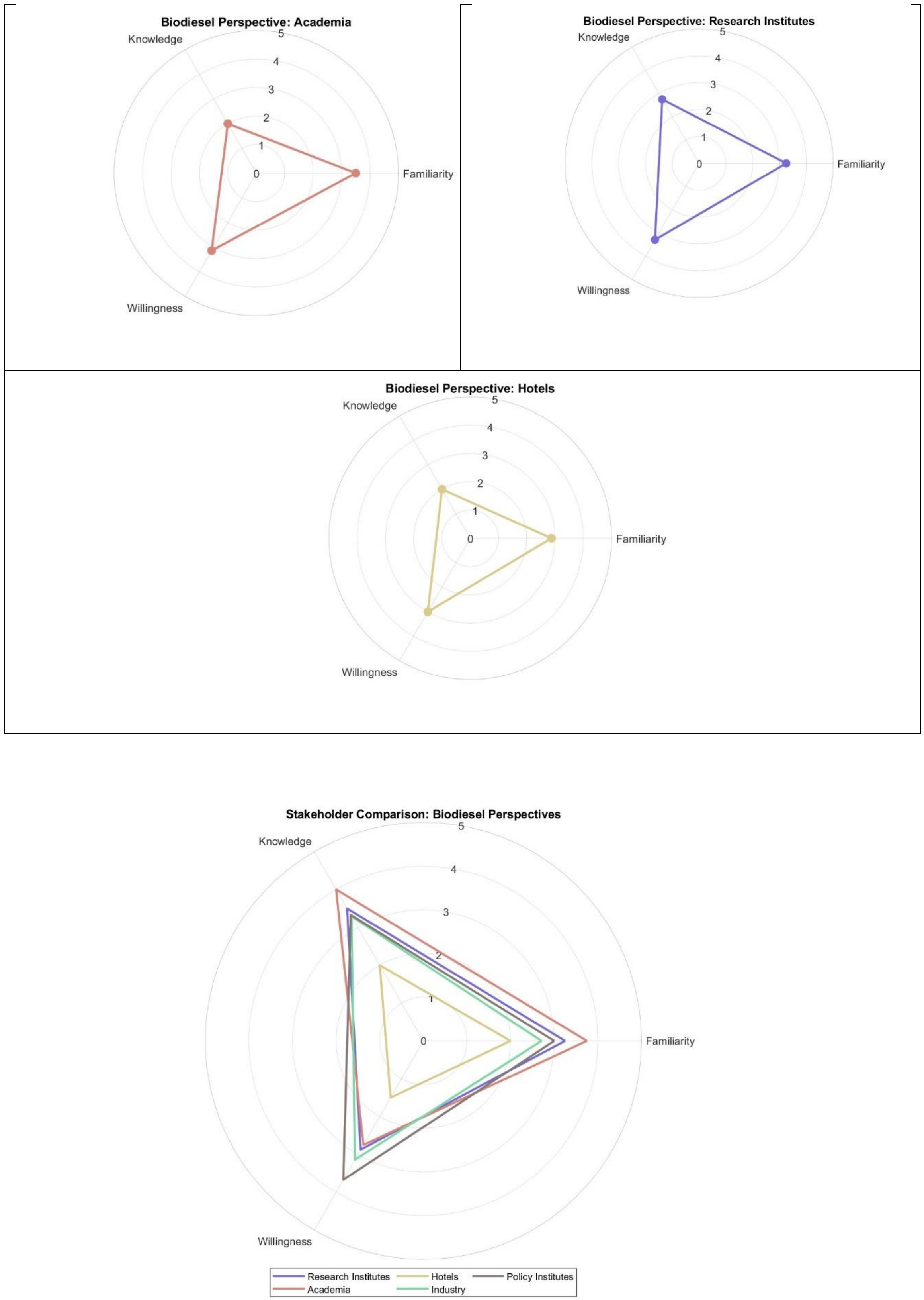


Figure 5.3 Comparison of the Perspective of different stakeholders

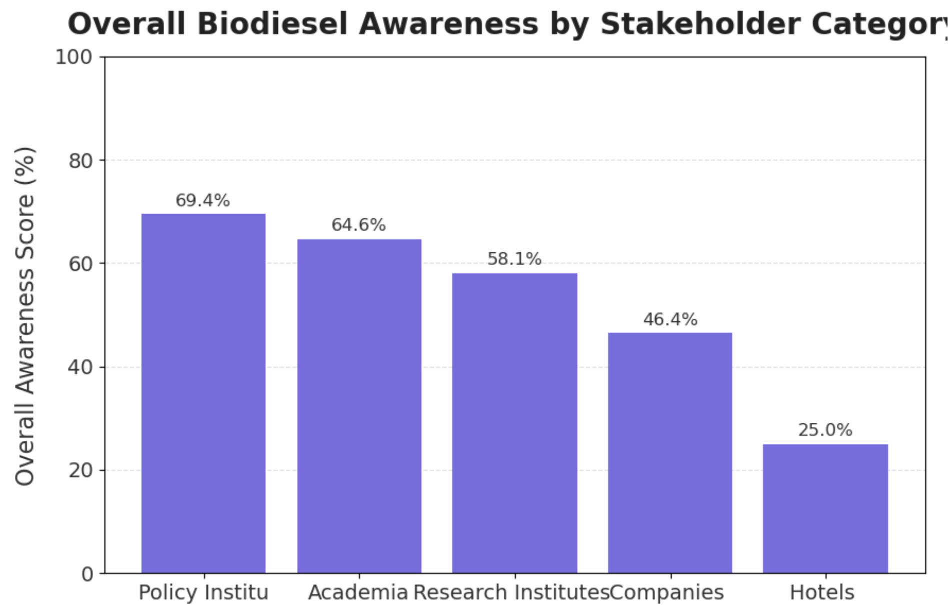


Figure 5.4 Awareness by sector

5.2.2 Correlation Analysis

The correlation analysis of biodiesel metrics shown in Figure *5.5* highlights key relationships between familiarity, knowledge, and willingness to adopt. A moderate correlation (0.5653) between familiarity and knowledge suggests that while many recognize biodiesel, they may lack a deep understanding of its benefits and applications, emphasizing the need for stronger educational efforts. The strong correlation (0.9636) between familiarity and willingness indicates that greater exposure significantly increases the likelihood of adoption, reinforcing the importance of targeted awareness campaigns. Similarly, the substantial correlation (0.7111) between knowledge and willingness shows that individuals with a deeper understanding of biodiesel are more likely to support its use, demonstrating the role of information in driving acceptance.

These findings highlight the need to close the gap between familiarity and knowledge through education, leverage awareness to enhance willingness, and strategically promote biodiesel's benefits via social media, industry events, and policy discussions to encourage broader adoption.

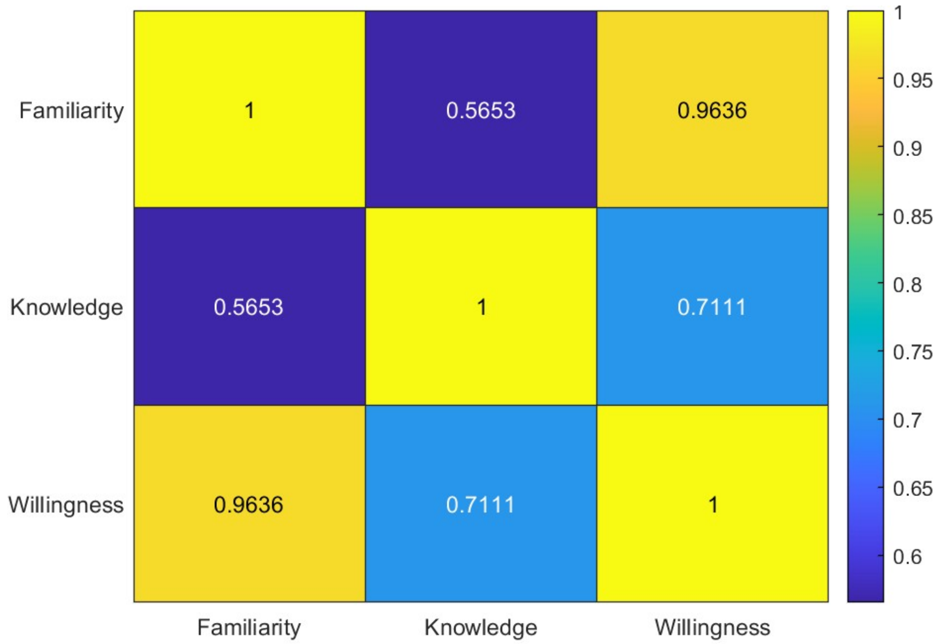


Figure 5.5 Correlation Analysis

5.2.3 Support for Biodiesel Policies and Social Impact Considerations

The level of support for government policies promoting biodiesel varies across sectors, as shown in the Figure 5.6. The Punjab government's 2018 policy clearly states that "Waste cooking oil shall only be used for biodiesel production rather than for other purposes, which are not sustainable."

Companies show the strongest support, with most responses clustered around levels 3 and 4, indicating that the private sector is open to biodiesel adoption, especially with the right incentives and regulations. Research institutes have a more balanced distribution, with notable support at levels 2 and 4, reflecting a moderate stance. Academia and hotels show mixed opinions, with responses spread across all levels, suggesting that while some stakeholders see the benefits, others have concerns about feasibility and implementation. Policy institutions mostly fall within levels 3 and 4, showing moderate to high support, though their overall engagement is lower than other sectors.

Concerns regarding the social impact of biodiesel production are prevalent across all sectors, with key considerations including land-use changes, environmental sustainability, economic feasibility, and consumer adaptability. These findings highlight the need for targeted awareness campaigns, financial incentives, and stronger policies to encourage biodiesel adoption. The strong support from companies suggests that the private sector could drive biodiesel initiatives if clear policies and support systems are in place. Additionally, increasing research funding and educational outreach could enhance engagement from academia and research institutions. While there is a positive trend towards biodiesel-supporting policies, addressing sector-specific concerns can further strengthen support and drive broader adoption.

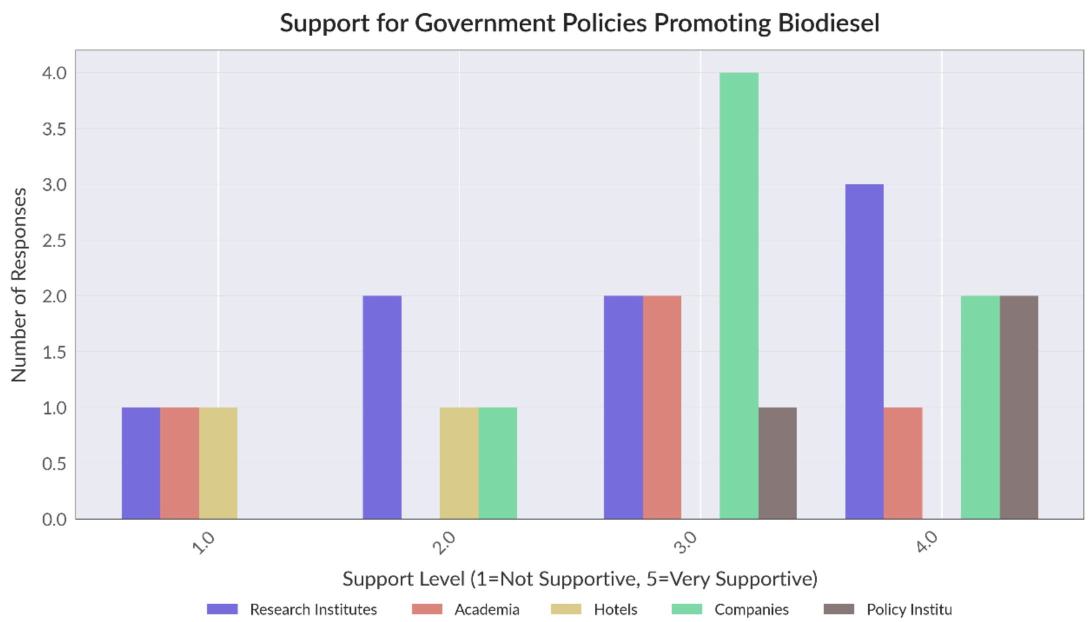


Figure 5.6 Support for Government Policy about Biodiesel

5.2.4 Key Concerns Regarding Biodiesel Usage

Each sector expresses unique concerns about the production, efficiency, and feasibility of biodiesel. The industrial sector is particularly focused on economic feasibility, as many businesses hesitate to adopt biodiesel due to concerns over cost and inconsistent supply chains. Additionally, challenges such as engine compatibility and potential modifications to existing machinery hinder adoption. The academic sector prioritizes technical and scientific challenges, advocating for further research, testing, and optimization before widespread implementation. Researchers emphasize the importance of identifying alternative feedstocks to enhance biodiesel's sustainability and cost-effectiveness.

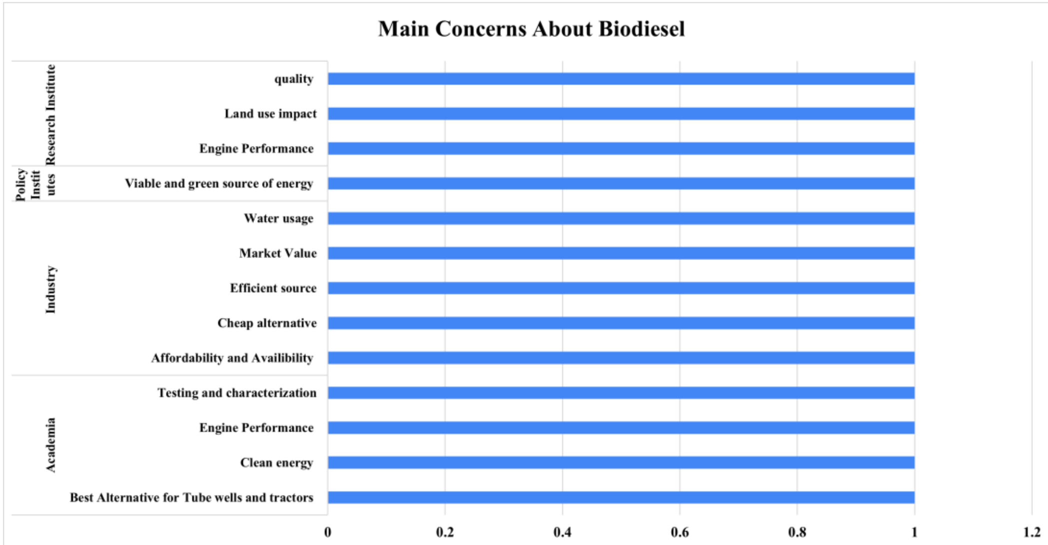


Figure 5.7 Major Concerns about Biodiesel

Policy institutions are primarily concerned with regulatory and environmental aspects, advocating for stronger policies, better financial incentives, and long-term strategic frameworks to promote biodiesel development. The restaurants faces practical challenges, including issues related to waste oil storage, disposal management, and limited knowledge about biodiesel applications. Addressing these challenges requires collaboration between policymakers, industries, and researchers, as well as technological advancements in biodiesel production and improved regulatory frameworks to ensure the feasibility and sustainability of biodiesel adoption.

5.2.5 Adoption and Practical Implementation of Biodiesel

Despite growing awareness, the practical adoption of biodiesel in real-world applications remains limited. Only a small number of companies have successfully integrated biodiesel into their operations, with most citing cost, market uncertainties, and supply chain limitations as primary barriers. Academic institutions primarily use biodiesel for research and experimental purposes, rather than practical applications on a larger scale.

The restaurants produces significant quantities of waste cooking oil, which could serve as a valuable resource for biodiesel production. However, few establishments currently participate in biodiesel-related initiatives due to a lack of awareness and logistical challenges. Although policy institutions recognize the advantages of biodiesel, they have limited direct involvement in its production or implementation. To enhance biodiesel adoption, key measures should include developing infrastructure, increasing government incentives, and ensuring that biodiesel is competitively priced compared to fossil fuels. Establishing efficient collection and distribution networks, enhancing financial support mechanisms, and expanding public and industrial awareness initiatives will be essential in driving broader biodiesel adoption.

5.3 Summary

This chapter presents the life cycle assessments associated with the biodiesel production along with the social analysis performed by conducting the survey-based analysis from different stakeholders. The first part focuses on environmental performance to assess the environmental impact of biodiesel production using the ReCiPe 2016 methodology, focusing on carbon emissions, resource use, and ecotoxicity. Waste cooking oil-based biodiesel shows the lowest environmental impact compared to other feedstocks. The second part focuses on the social analysis evaluates stakeholder awareness, policy support, and concerns related to biodiesel adoption.

Chapter 6 Data driven Machine Learning Results

This chapter provides a comprehensive evaluation of the machine learning model's performance, emphasizing its accuracy in predicting biodiesel yield with minimal error, estimating emissions based on feedstock characteristics, and forecasting production costs per liter while accounting for fluctuations.

6.1 ANN Modelling

The ANN predictive modeling was conducted using a dataset of 100 observations generated by using the design of experiment methodology as mentioned in section 3.9.1, attached in Appendix I. The regression plot shown in Figure 6.1 of the ANN model illustrates the relationship between experimental and predicted values across training, validation, and testing datasets. The correlation coefficient (R) values obtained for these datasets were 0.99868 (training), 0.98991 (validation), 0.96941 (testing), and 0.9954 (overall), all of which are very close to 1. These high R-values indicate the strong predictive accuracy of the model, confirming its ability to replicate experimental data effectively.

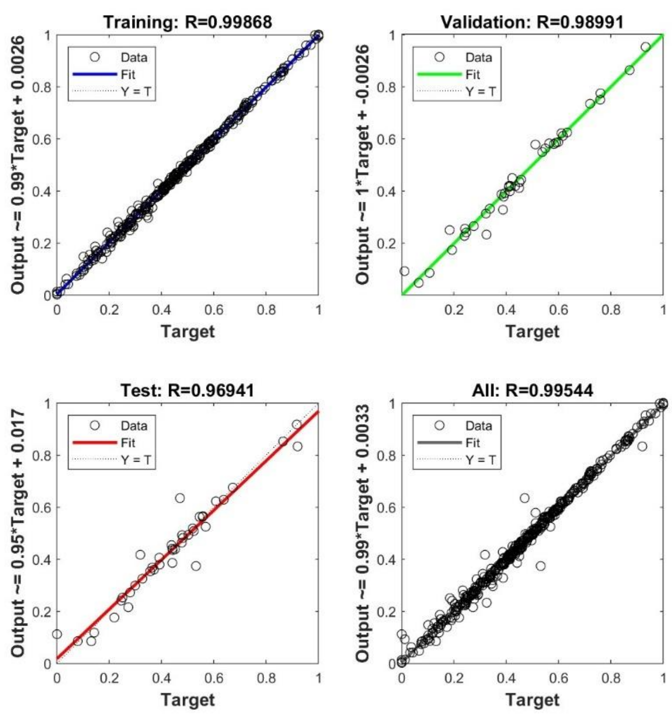


Figure 6.1 Regression plots of Training, Validation, Test and All data

The model successfully predicts emissions, fuel yield, and cost per liter of biodiesel, considering the variability in feedstock free fatty acid (FFA) content and availability. The predicted results closely align with experimental data in terms of biodiesel yield, life cycle assessment (LCA) results related to greenhouse gas (GHG) emissions, and fuel cost per liter. This consistency highlights the ANN model's reliability in real-world applications.

The validation performance of the ANN model over multiple epochs is illustrated in Figure (epochs), where the best performance is achieved at epoch 18 with a mean squared error (MSE) of 0.000637. This low MSE value signifies minimal error, demonstrating the high accuracy of the ANN model. In statistical modeling, a lower MSE indicates better predictive performance. Additionally, the error histogram Figure 6.4 presents the distribution of errors between experimental and predicted values, further supporting the model's accuracy. The training state graph Figure 6.2 shows gradient magnitude fluctuations across 24 epochs, with six validation checks, reinforcing the model's stability during training.

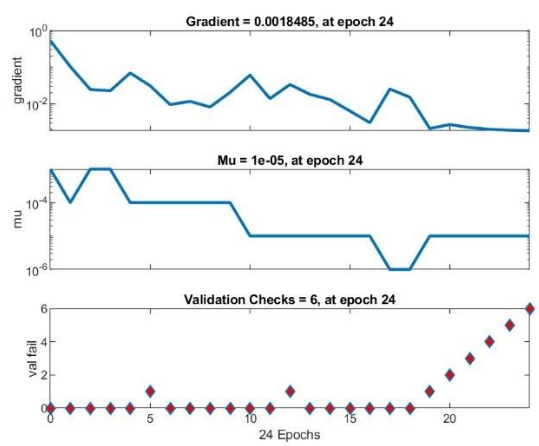


Figure 6.2 Validation Performance

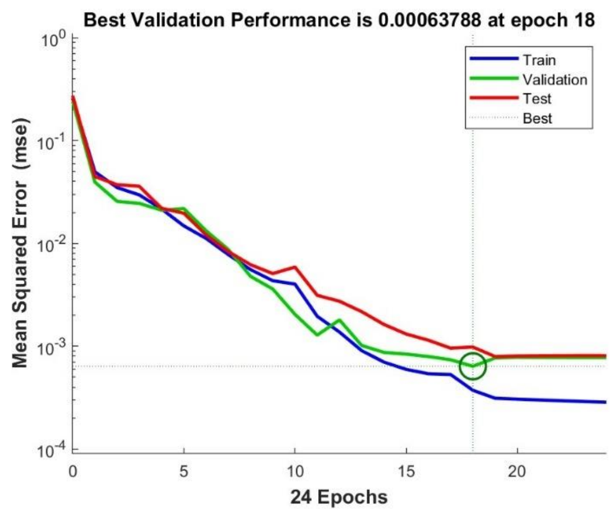


Figure 6.3 Model Performance

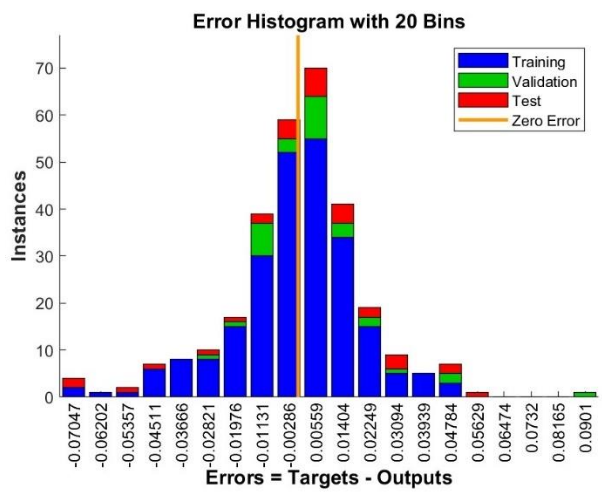


Figure 6.4 Error Histogram

Overall, the results confirm that the ANN model provides a highly accurate and reliable prediction of biodiesel yield, emissions, and cost per liter, making it a valuable tool for optimizing biodiesel production from various feedstocks.

6.2 Optimization and Performance Evaluation of the Predictive Model

Sensitivity analysis was conducted to evaluate the impact of tuning the number of neurons and the division of input data on the accuracy of predicting biodiesel yield, emissions, and cost per liter. The model was tested using multiple experimental runs, varying the number of neurons in the hidden layers within a specified range while adjusting the data splitting ratios. The correlation coefficient (R) and mean squared error (MSE) were analyzed for each run to assess predictive accuracy.

The analysis revealed that Run 6, which utilized a 10-6 neuron configuration with a 0.8-0.1-0.1 data splitting ratio, achieved a highly accurate yield prediction with an R-value of 0.9. However, it was not suitable for predicting emissions and cost. Similarly, Run 4, configured with 10-8 neurons and a 0.7-0.15-0.15 splitting ratio, demonstrated accuracy in predicting both yield and cost, each with an R-value of 0.8, but was less effective in emissions prediction. On the other hand, Run 9, using a 6-6 neuron arrangement with the 0.8-0.1-0.1 splitting ratio, provided the most precise prediction for emissions with an R-value of 0.9, though it was less accurate for yield and cost.

Table 6.1 Sensitivity Analysis of ANN Model

Run	**Number of Neurons**		**Splitting of data**			**MSE**		**R^2 of Predicted Data**			**MSE in Predicted data**		
	1st layer	**2nd Layer**	**Training data**	**Validation Data**	**Test Data**	**Performance MSE**	**Test MSE**	**Yield R^2**	**Cost R^2**	**Emissions R^2**	**Yield Error**	**Cost Error**	**Emissions Error**
1	8	6	0.8	0.1	0.1	0.000532	0.001732	0.8923	0.9252	0.8241	0.000608	0.074552	0.000608
2	8	6	0.7	0.15	0.15	0.004496	0.023732	0.151	0.444	0.2071	0.010335	0.05267	0.010335
3	10	8	0.8	0.1	0.1	0.001421	0.007939	0.4275	0.3594	0.2132	0.003114	0.022868	0.003114
4	10	8	0.7	0.15	0.15	0.0012	0.005049	0.8958	0.8953	0.3465	0.000978	0.053484	0.000978
5	10	6	0.7	0.15	0.15	0.001724	0.004077	0.299	0.1147	0.2752	0.004566	0.02117	0.004566
6	10	6	0.8	0.1	0.1	0.001724	0.004077	0.9925	0.2199	0.4914	0.00038	0.16749	0.00038
7	6	4	0.7	0.15	0.15	0.004254	0.005261	0.1467	0.0163	0.5577	0.005002	0.025427	0.005002
8	6	4	0.8	0.1	0.1	0.001737	0.00552	0.678	0.8853	0.5243	0.002255	0.004366	0.002255
9	6	6	0.8	0.1	0.1	0.000524	0.002676	0.7408	0.182	0.9685	0.001549	0.144374	0.001549
10	6	6	0.7	0.15	0.15	0.001262	0.003452	0.2427	0.1471	0.0331	0.004157	0.10021	0.004157
11	5	5	0.8	0.1	0.1	0.000422	0.001916	0.6191	0.0419	0.7461	0.002032	0.113788	0.002032
12	4	4	0.8	0.1	0.1	0.000646	0.002334	0.5628	0.1749	0.4627	0.003185	0.209646	0.003185
13	4	2	0.8	0.1	0.1	0.070365	0.035496	0.1391	0.8746	0.0762	0.004794	0.006988	0.004794
14	2	2	0.8	0.1	0.1	0.017092	0.021165	0.1751	0.0509	0.0771	0.004794	0.006988	0.004794

Based on the sensitivity analysis, the optimal ANN model was determined to have 8 neurons in the first hidden layer, 6 neurons in the second hidden layer, and a 0.8-0.1-0.1 data splitting ratio for training, validation, and testing, respectively. The correlation coefficient values for this selected model were 0.8923 for yield, 0.9252 for cost per liter, and 0.8241 for emissions per liter of biodiesel. The calculated MSE values were 0.000532 for performance and 0.001732 for test MSE, confirming the model's accuracy in predicting the key biodiesel production parameters.

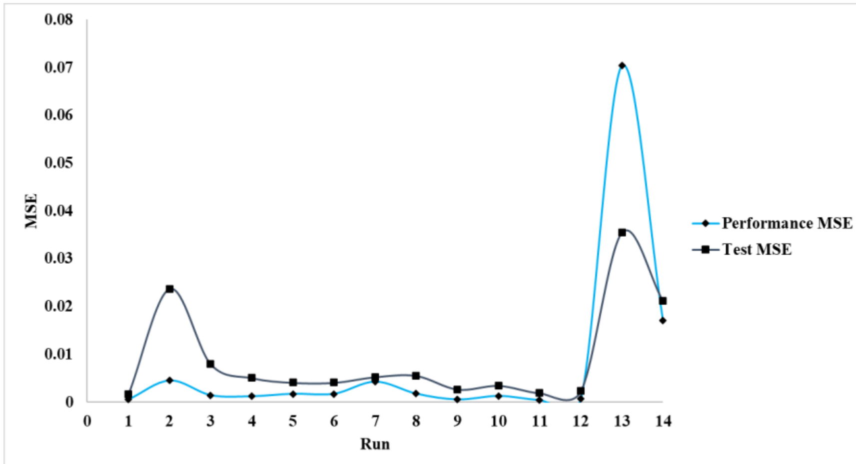


Figure 6.5 Performance and Test MSE vs Run of experiments

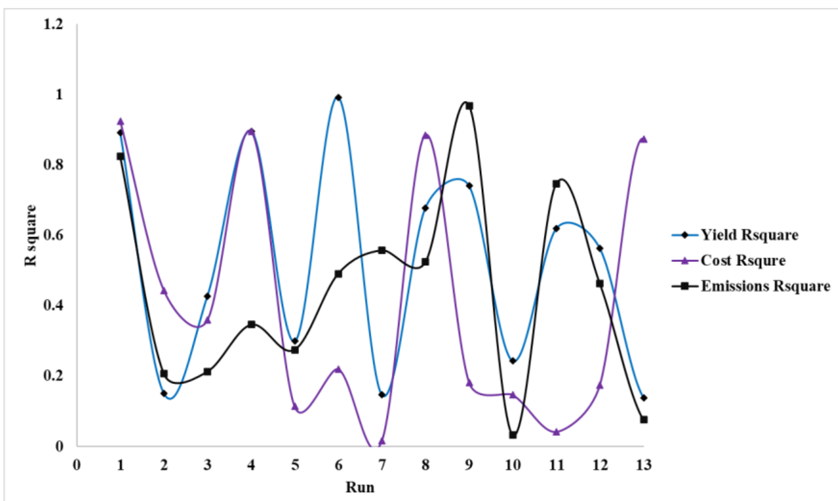


Figure 6.6 Correlation factors of output vs Run of Experiments

6.3 Yield Prediction

The regression plot as shown in Figure 6.7 below demonstrates the correlation between the experimental and predicted biodiesel yield using the ANN model. The coefficient of determination (R^2 = 0.9235) signifies a strong relationship between the two datasets, confirming the model's high predictive accuracy.

The data points are closely aligned with the trendline, indicating that the model effectively captures the yield variations. However, minor deviations suggest slight discrepancies, possibly due to experimental uncertainties or variations in feedstock properties.

Overall, the high R^2 value validates the model's reliability in estimating biodiesel yield, making it a useful tool for optimizing feedstock selection and refining process parameters.

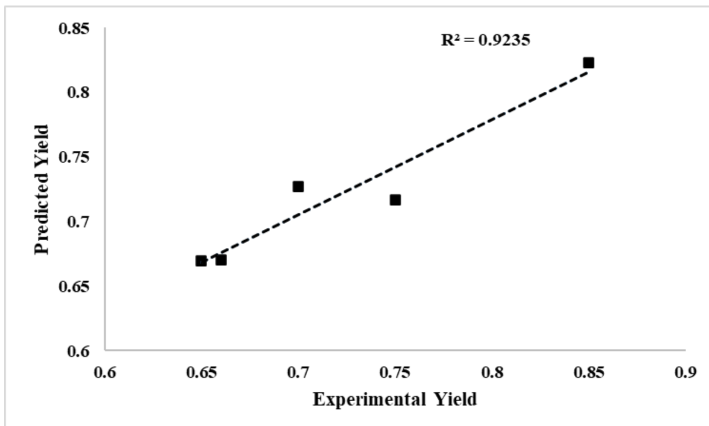


Figure 6.7 Experimental vs Predicted Yield

6.4 Fuel Cost Per liter

The regression plot as shown in Figure *6.8* represents the relationship between the actual and predicted fuel cost using the ANN model. The coefficient of determination (R^2 = 0.9252) suggests a strong agreement between the predicted and experimental values, highlighting the model's accuracy in estimating fuel costs.

Most data points align well with the trendline, indicating the model’s capability to capture cost variations effectively. However, minor discrepancies may be attributed to fluctuations in feedstock prices, processing costs, or inherent model limitations. The high R^2 value confirms the model’s reliability in forecasting fuel cost, making it a useful tool for economic analysis in biofuel production.

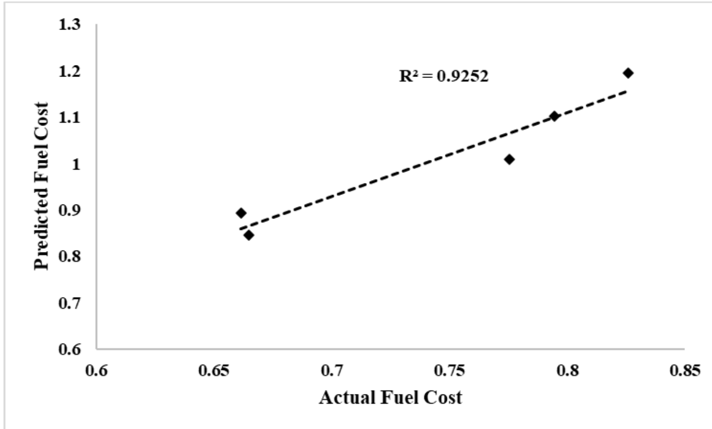


Figure 6.8 Actual Fuel Cost vs Predicted Fuel Cost

6.5 Prediction of Emissions Per liter of Biodiesel

The regression plot as shown in Figure 6.9 represents the relationship between actual and predicted Life Cycle Assessment (LCA) emissions using the ANN model, with a coefficient of determination (R^2 = 0.8241). This value suggests a reasonably strong correlation, though with some variations, indicating the complexity of accurately modeling emissions across a fuel's life cycle.

LCA emissions account for the total environmental impact of fuel production, including feedstock cultivation, processing, transportation, and combustion. The observed deviations from the trendline could stem from factors such as variations in feedstock type, energy consumption during processing, and transportation emissions. Since different waste oil feedstocks have varying Free Fatty Acid (FFA) content and processing efficiencies, slight discrepancies in emissions predictions are expected.

As with fuel yield, higher FFA values contributed to higher emissions due to increased methanol consumption and longer processing times. Additionally, feedstock quantity played a role in emissions predictions, as smaller quantities often required more transportation, resulting in higher transportation-related emissions. By accounting for these logistical factors, the model provided valuable insights into how feedstock characteristics and transportation decisions can impact the carbon footprint of biodiesel production. Despite the minor inconsistencies, the model effectively captures the overall emissions trend, making it a valuable tool for estimating the environmental footprint of biofuels.

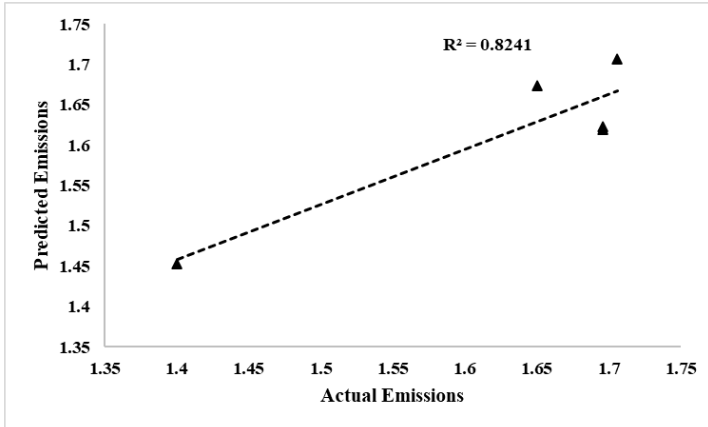


Figure 6.9 Actual emissions per liter vs Predicted emissions per liter

6.6 Summary

This chapter discusses the application of machine learning, particularly ANN models, in predicting biodiesel yield, emissions, and fuel cost. The model is trained using data, achieving high accuracy with correlation coefficients close to 1. Sensitivity analysis is performed to optimize the model, demonstrating its efficacy in improving decision-making for biodiesel production. The findings suggest that incorporating the machine learning in biofuels can enhance process efficiency by optimizing the supply chain and sustainability in bioenergy.

Chapter 7 Conclusion and Recommendations

7.1 Conclusion

This study presented experimental characterization and environmental impact of biodiesel production from local waste fats. The study developed to produce biodiesel from oils of different origins with the purpose of on-ground actual evaluation of impact parameters. The underlying idea is to compare the quality and composition of biodiesel produced from different waste oil collected from different sources and evaluate their actual relative impacts in terms of carbon footprints.

It is noted that the higher value of acid number implies higher frequency of oil usage for cooking and frying in restaurants resulting in lesser yields of biodiesel and higher carbon footprint. The maximum yield (with conversion efficiency of 85%) of biodiesel was recorded for the sample with acid value 3.5mgKOH/g with heating values of 35.8MJ/kg. Moreover, the feed stocks and obtained biodiesel of the difference sources revealed variations of different functional groups in oil and their relative intensities.

The FTIR analysis verified the successful transformation of oils into biodiesel through the transesterification process, while supported by GC-MS analysis for the presence of fatty acid methyl esters (FAMEs) in the biodiesel. The biodiesel spectra indicated FAME production, marked by the disappearance of the 1377 cm^{-1} peak and changes in intensity at 1363 cm^{-1}, 1436 cm^{-1}, and 1198 cm^{-1}. The prominent peak at ~1743 cm^{-1} confirmed the formation of esters and the conversion of triglycerides into biodiesel.

GC-MS analysis showed that Type A biodiesel, with a higher proportion of saturated FAMEs linked with the higher heating value observed, whereas Types B, C, and D contained a combination of saturated and unsaturated FAMEs.

Comparison of the life cycle assessments of the resultant biodiesels demonstrate that the chemical characteristics of feedstock used has a considerable impact on the environmental footprint of biodiesel production. The results shows that type A, B, C and D has 70%, 64%, 63% and 65% less carbon foot print than fossil diesel respectively. This outcome is related to factors such as lower Free Fatty Acid (FFA) levels of type A (high-end restaurants), which results in less chemical use, energy consumption, and transportation for the overall production process.

Large chains & higher rated hotels are identified as excellent candidates to earn higher carbon rewards for utilization of used cooking oils. While even the highly burnt cooking oil is still a viable resource for biodiesel despite relatively higher carbon footprint as around 5% higher emissions are seen in their re-use for bio-diesel formation.

Social analysis highlights the crucial role of awareness, knowledge, and strategic communication in driving biodiesel adoption. While familiarity with biodiesel is relatively high across sectors, gaps in knowledge and general awareness hinder widespread acceptance and implementation. Strong correlations between familiarity, knowledge, and willingness to adopt suggest that targeted educational initiatives and awareness campaigns can significantly enhance biodiesel adoption. Strengthening partnerships between industry, government, and academia, along with leveraging social media, industry events, and policy discussions, will be key to bridging these gaps. By addressing sector-specific concerns and promoting clear policy frameworks, biodiesel adoption can be accelerated, contributing to more sustainable energy solutions.

The implementation of Artificial Neural Networks (ANN) for predicting yield, fuel cost, and Life Cycle Assessment (LCA) emissions has demonstrated a high level of accuracy and reliability. The strong correlation between experimental and predicted values, particularly in yield ($R^2 = 0.9235$) and fuel cost ($R^2 = 0.9252$), confirms the model's effectiveness in capturing key parameters influencing biodiesel production. While the emissions model ($R^2 = 0.8241$) showed slightly more variation, it still provided valuable insights into the environmental impact of biofuel production.

The sensitivity analysis further validated the importance of optimizing the number of neurons and data division for improving prediction accuracy. The selected ANN model, with 8 neurons in the first hidden layer, 6 in the second hidden layer, and a data split of 0.8-0.1-0.1, proved to be the most effective in predicting yield, cost, and emissions.

Overall, this study highlights the potential of ANN-based modeling in biofuel research, offering a data-driven approach for optimizing production, reducing environmental impact, and enhancing energy security. By leveraging waste oils for biodiesel production, this research aligns with global sustainability goals and promotes the adoption of cleaner fuels in both road transportation and other industrial sectors. Future improvements, such as integrating hybrid models and additional environmental factors, could further refine predictive accuracy and support large-scale biofuel implementation.

Biodiesel production from waste cooking oil presents a cost-effective solution, reducing dependence on imported fossil fuels. Adoption of biodiesel on local scale and engagement of different key stake holders could support local economies by promoting waste-to-energy initiatives in the renewable energy sector. However, policy interventions, incentives from government in tax credits and investment in the bioenergy are necessary to establish structured biodiesel production and utilization frameworks.

The scalability of biodiesel production can be improved by utilizing local waste resources, such as used cooking oils, while incorporating renewable energy technologies like solar-powered systems and bioenergy to enhance sustainability. This approach supports global renewable energy objectives, such as SDG 7, and aligns with regional initiatives like the Punjab Government Policy 2018, which emphasizes the valorization of waste oils, and the EU Renewable Energy Directive (RED II), which advocates for circular economy practices. Future developments should focus on advancing efficient catalysts, optimizing methanol recovery, integrating carbon capture technologies, and conducting comprehensive lifecycle with techno-economic analyses to ensure long-term viability and alignment with net-zero goals.

7.2 Recommendations

To enhance the feasibility and large-scale adoption of biodiesel, several key recommendations are proposed.

Optimizing feedstock selection and production processes is crucial. Prioritizing waste cooking oil and non-food waste sources minimizes environmental impact and prevents food-versus-fuel competition. Additionally, developing blended biodiesel formulations such as B20 and B50 can help balance fuel efficiency and emissions reduction. Advancing catalyst research is also essential to improving conversion efficiency and reducing processing costs.

Technological advancements in biodiesel production can further streamline the process and improve efficiency. Utilizing heterogeneous catalysts minimizes waste and enhances reusability, making the production process more sustainable. Additionally, implementing ultrasonic-assisted transesterification can enhance reaction kinetics, reducing processing time and making biodiesel production more cost-effective.

Environmental and policy interventions are necessary to encourage industrial adoption and sustainability. Governments should introduce incentives and subsidies for biodiesel production from waste sources to make it a financially viable alternative to fossil fuels. Establishing regulatory frameworks is also essential to ensure quality standards and sustainability benchmarks. Furthermore, promoting carbon credit mechanisms can incentivize biofuel adoption and reward industries for reducing emissions.

Integration with existing energy infrastructure is another critical step. Expanding biodiesel use in public transport, agriculture, and industrial applications can facilitate a gradual transition towards cleaner energy. Additionally, fostering collaborations between research institutions and policymakers can help standardize biodiesel blending regulations, ensuring consistency and efficiency across industries.

Leveraging machine learning and artificial intelligence can significantly improve biodiesel production and distribution. Predictive modeling can be used for biodiesel yield estimation, cost analysis, and emissions forecasting, optimizing production efficiency. AI-driven supply chain management can also enhance the logistics of biodiesel distribution, ensuring a more efficient and cost-effective supply network.

Finally, increasing public awareness and fostering industry collaboration are essential to promoting biodiesel adoption. Awareness campaigns can educate stakeholders on the environmental and economic benefits of biodiesel, encouraging wider acceptance. Public-private partnerships can further drive research, innovation, and commercialization of biodiesel technology, ensuring its long-term success as a sustainable energy alternative.

7.3 Future Research Recommendations

While this study provides critical insights, further research is needed to:

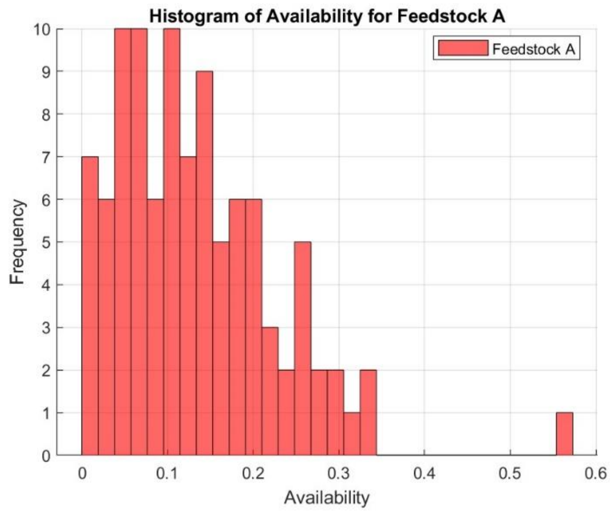
- Improve biodiesel stability and cold-weather performance to enhance usability in diverse climates.
- Investigate hybrid biofuel technologies integrating biodiesel with solar and hydrogen-based energy systems.
- Enhance NOx emissions control strategies, such as exhaust gas recirculation (EGR) and catalytic converters.

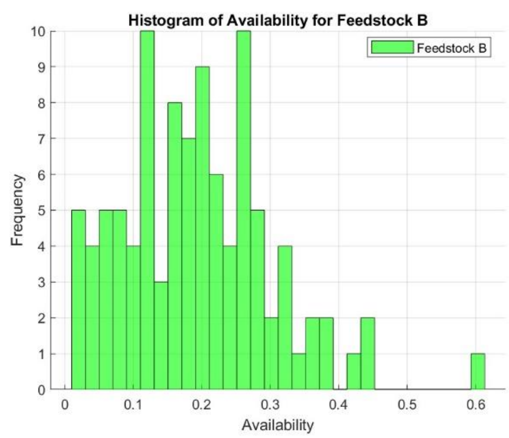
By implementing these recommendations, biodiesel can play a pivotal role in achieving energy security, reducing carbon emissions, and promoting environmental sustainability. The results of this study serve as a foundational reference for policymakers, industry leaders, and researchers seeking to advance biodiesel adoption in the global energy landscape.

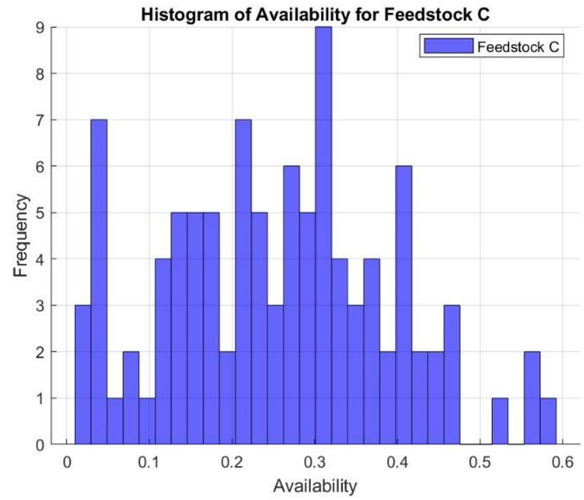
Appendix I

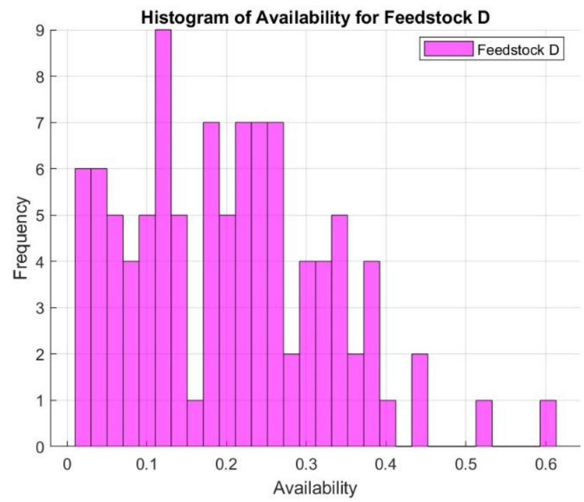
Histograms Data Set Used in Machine Learning

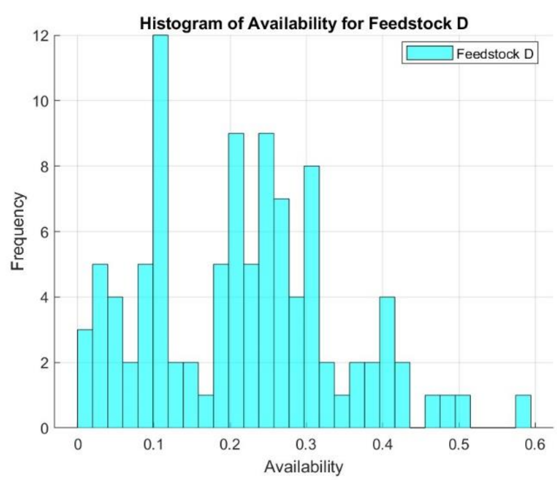
Availability of Feedstocks from different sources



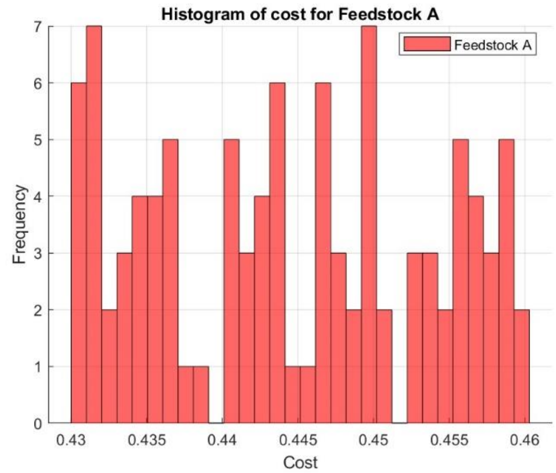


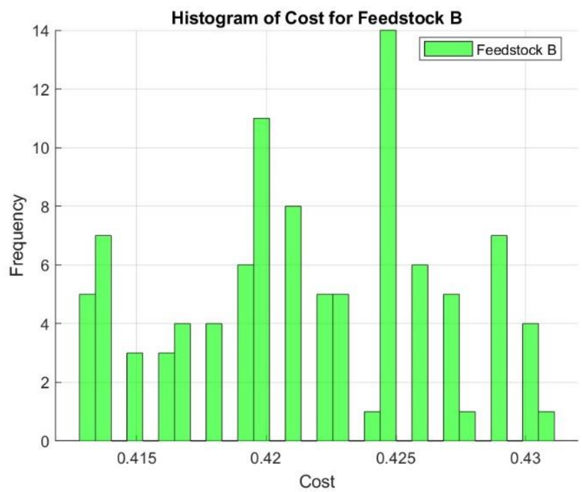

Histogram of Availability for Feedstock C
Feedstock C
Frequency
Availability
0 1 2 3 4 5 6 7 8 9
0 0.1 0.2 0.3 0.4 0.5 0.6

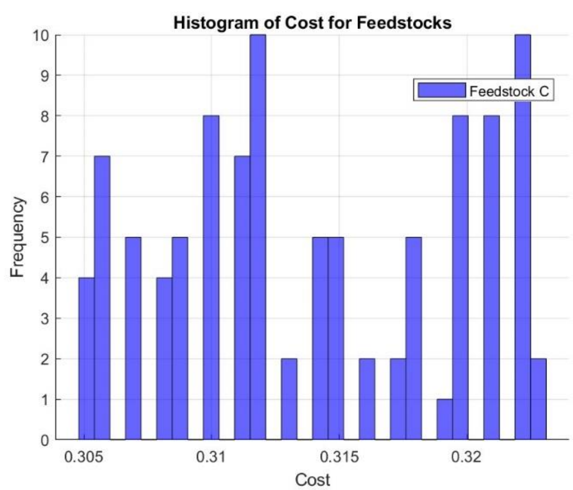

Histogram of Availability for Feedstock D
Feedstock D
Frequency
Availability
0 1 2 3 4 5 6 7 8 9
0 0.1 0.2 0.3 0.4 0.5 0.6

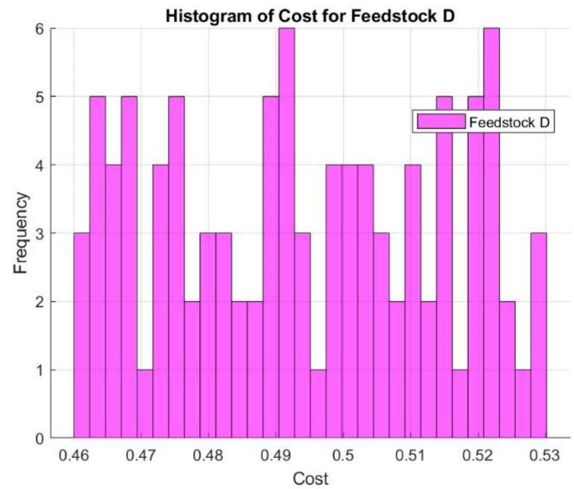

Histogram of Availability for Feedstock D
Feedstock D
Frequency
Availability
0 2 4 6 8 10 12
0 0.1 0.2 0.3 0.4 0.5 0.6

Cost of Feedstocks from different sources








Histogram of Cost for Feedstock D
Feedstock D
Frequency
Cost
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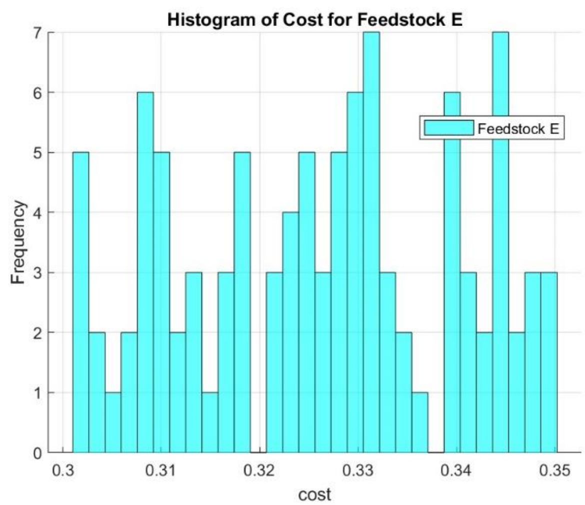
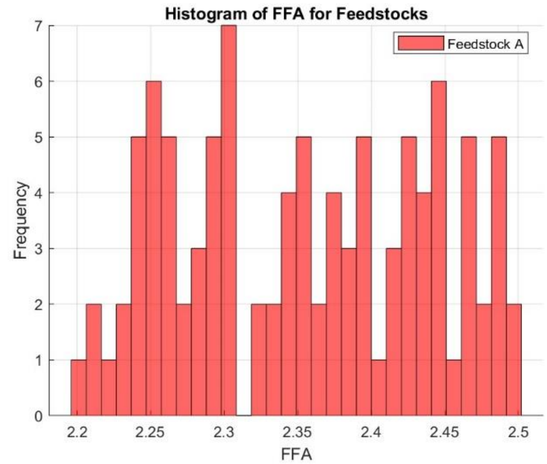
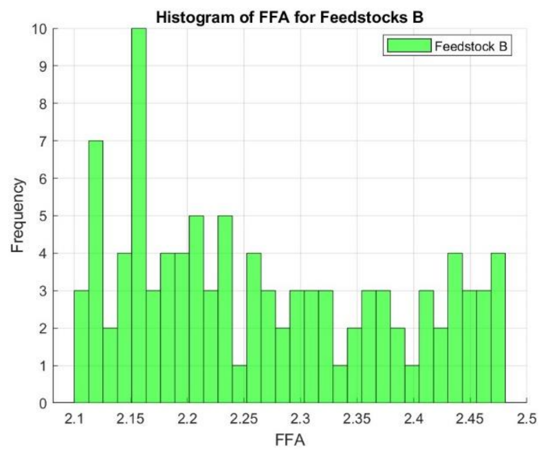
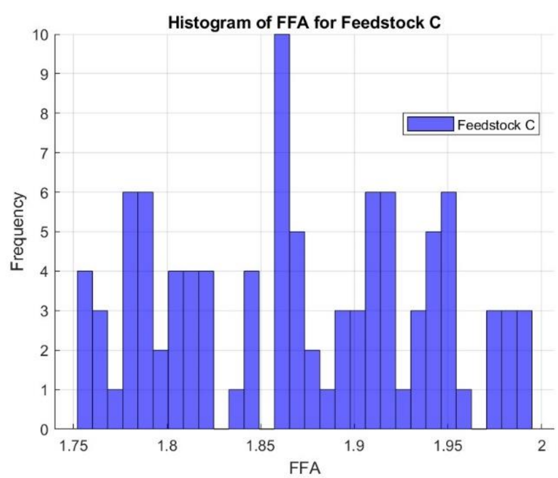
0.47
0.48
0.49
0.5
0.51
0.52
0.53
0
1
2
3
4
5
6

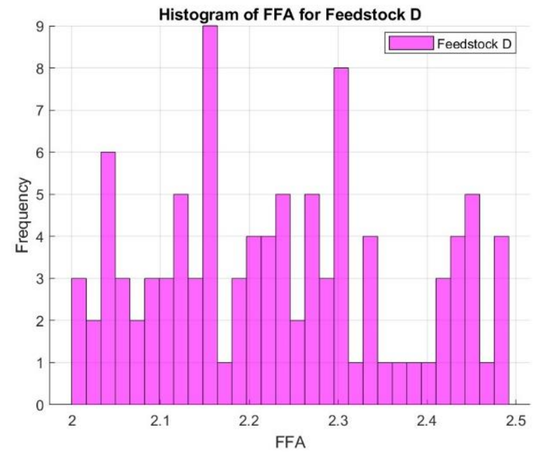

Histogram of Cost for Feedstock E
Feedstock E
Frequency
cost
0.3
0.31
0.32
0.33
0.34
0.35
0
1
2
3
4
5
6
7

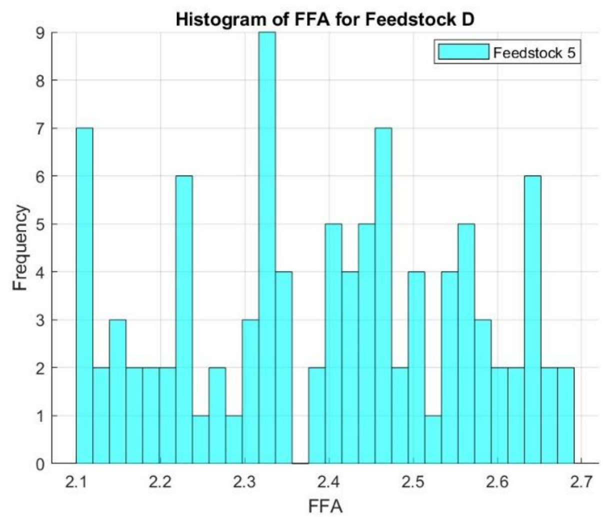
FFAs of Feedstocks from different Sources








Histogram of FFA for Feedstock D
Feedstock D
Frequency
FFA
0
1
2
3
4
5
6
7
8
9
2
2.1
2.2
2.3
2.4
2.5


Histogram of FFA for Feedstock D
Feedstock 5
Frequency
FFA
0
1
2
3
4
5
6
7
8
9
2.1
2.2
2.3
2.4
2.5
2.6
2.7

Appendix II

Social Analysis Questionnaire for Academia

Sociodemographic and Socioeconomic Data

- Name
- University Name
- What is your role in academia?
- What is your field of expertise?

Knowledge

- How familiar are you with biodiesel as an alternative fuel? (Scale: Not familiar - Very familiar)
- Do you know the environmental benefits of using biodiesel compared to conventional diesel? (Yes/No)
- Are you aware of the different feedstocks used for biodiesel production? (Yes/No)
- How knowledgeable are you about the production process of biodiesel? (Scale: Not Knowledgeable - Very Knowledgeable)
- What sources of information have influenced your understanding of biodiesel?

Attitude

- How important do you think it is to use renewable energy sources like biodiesel? (Scale: Not Important - Very Important)
- Do you believe that biodiesel is a viable alternative to conventional diesel? (Yes/No)
- How supportive are you of government policies promoting biodiesel use? (Scale: Not Supportive - Very Supportive)
- How concerned are you about the potential social impacts of biodiesel on local communities? (Scale: Not Concerned - Very Concerned)

Practice

- Has your institute ever used biodiesel in research or academic projects? (Yes/No)
- How often do you consider using biodiesel in your academic work when available? (Never, Rarely, Sometimes, Often)

- Would you be willing to conduct research on biodiesel in your university? (Yes/No)
- What are your main concerns about the use of biodiesel?

View Point

- How likely are you to recommend biodiesel to others in the academic community? (Scale: Not likely - Very likely)
- What factors influence your research on biodiesel?
- What challenges do you foresee in the production of biodiesel?
- What measures would you suggest for the adoption and production of biodiesel?
- What incentives would encourage you to increase the use and production of biodiesel?

Survey Questionnaires for Research Institutes

Sociodemographic and Socioeconomic Data

- Name
- Research Institute Name
- What is the primary focus of your research institute?
- What is your role in the institute?

Knowledge

- How familiar is your institute with biodiesel as an alternative fuel for agricultural machinery or other purposes? (Scale: Not familiar - Very familiar)
- Does your institute know the environmental benefits of using biodiesel compared to conventional diesel? (Yes/No)
- Is your institute aware of the different feedstocks used for biodiesel production? (Yes/No)
- How knowledgeable are you about the production process of biodiesel? (Scale: Not Knowledgeable - Very Knowledgeable)
- What sources of information have influenced your understanding of biodiesel?

Attitude

- How important do you think it is to use renewable energy sources like biodiesel in your relevant sector? (Scale: Not Important - Very Important)

- Do you believe that biodiesel is a viable alternative to conventional diesel? (Yes/No)
- How supportive are you of government policies promoting biodiesel use? (Scale: Not Supportive - Very Supportive)
- How concerned are you about the potential social impacts of biodiesel on local communities? (Scale: Not Concerned - Very Concerned)

Practice

- Has your institute ever used biodiesel in its agricultural research or projects? (Yes/No)
- How often does your institute consider using biodiesel in machinery when available? (Never, Rarely, Sometimes, Often)
- Is there any financial support or awareness project ongoing regarding the practice and production of biodiesel? (Yes/No)
- Is there any policy your institute has worked on, or from the government side, to invest in biodiesel production in support of sustainable energy? (Yes/No)

View Point

- How likely is your institute to recommend biodiesel to others in the agricultural research community? (Scale: Not likely - Very likely)
- What factors influence your institute's decision to use or not use biodiesel in research and operations?
- What challenges do you foresee in the production of biodiesel for use?
- What measures would your institute suggest for the adoption and production of biodiesel?
- What incentives would encourage your institute to increase the use and production of biodiesel?

Survey Questionnaires for Policy Institutes

Sociodemographic and Socioeconomic Data

- Name
- Institute Name
- What is the main focus of your policy institute?
- What is your position in the institute?

Knowledge

- How familiar is your institute with biodiesel as an alternative fuel? (Scale: Not familiar - Very familiar)
- Does your institute know the environmental benefits of using biodiesel compared to conventional diesel? (Yes/No)
- Is your institute aware of the different feedstocks used for biodiesel production? (Yes/No)
- How knowledgeable are you about the production process of biodiesel? (Scale: Not Knowledgeable - Very Knowledgeable)
- What sources of information have influenced your understanding of biodiesel?

Attitude

- How important do you think it is to use renewable energy sources like biodiesel? (Scale: Not Important - Very Important)
- Do you believe that biodiesel is a viable alternative to conventional diesel? (Yes/No)
- How supportive are you of government policies promoting biodiesel use? (Scale: Not Supportive - Very Supportive)
- How concerned are you about the potential social impacts of biodiesel on local communities? (Scale: Not Concerned - Very Concerned)

Practice

- How often do you consider using biodiesel when available? (Never, Rarely, Sometimes, Often)
- Is there any financial support or awareness project ongoing regarding the practice and production of biodiesel? (Yes/No)
- Is there any policy your institute has worked on, or from the government side, to invest in biodiesel production in support of sustainable energy? (Yes/No)

View Point

- What factors influence your institute’s decision to support biodiesel programs?
- What challenges do you foresee in the production of biodiesel for use?
- What measures would your institute suggest for the adoption and production of biodiesel?

- What incentives would encourage your institute to increase the use and production of biodiesel?

Survey Questionnaires for Industry

Sociodemographic and Socioeconomic Data

- Name
- Company Name
- What is the size of your company?
- What industry does your company operate in?
- What is your position in the company?

Knowledge

- How familiar is your company with biodiesel as an alternative fuel? (Scale: Not familiar - Very familiar)
- Does your company know the environmental benefits of using biodiesel compared to conventional diesel? (Yes/No)
- Is your company aware of the different feedstocks used for biodiesel production? (Yes/No)
- How knowledgeable is your company about the production process of biodiesel? (Scale: Not Knowledgeable - Very Knowledgeable)
- What sources of information have influenced your company's understanding of biodiesel?

Attitude

- How important does your company think it is to use renewable energy sources like biodiesel? (Scale: Not Important - Very Important)
- Does your company believe that biodiesel is a viable alternative to conventional diesel? (Yes/No)
- How supportive is your company of government policies promoting biodiesel use? (Scale: Not Supportive - Very Supportive)
- How concerned is your company about the potential social impacts of biodiesel on local communities? (Scale: Not Concerned - Very Concerned)

Practice

- Has your company ever used biodiesel in its operations? (Yes/No)
- How often does your company consider using biodiesel when available? (Never, Rarely, Sometimes, Often)
- Would your company be willing to pay more for biodiesel if it meant supporting sustainable energy? (Yes/No)
- Would your company be willing to invest in biodiesel production on a pilot scale if it meant supporting sustainable energy? (Yes/No)

View Point

- How likely is your company to recommend biodiesel to others? (Scale: Not likely - Very likely)
- What factors influence your company's decision to use or not use biodiesel?
- What challenges do you foresee in the production of biodiesel for use?
- What measures would your company suggest for the adoption and production of biodiesel?
- What incentives would encourage your company to increase its use and production of biodiesel?

Survey Questionnaires for Hotels and Suppliers

Sociodemographic and Socioeconomic Data

- Name
- Hotel/Restaurant Name
- What is your role?

Knowledge

- How familiar are you with biodiesel as an alternative fuel? (Scale: Not familiar - Very familiar)
- Do you know the environmental benefits of using biodiesel compared to conventional diesel? (Yes/No)
- Are you aware that waste cooking oil can be used for biodiesel production? (Yes/No)
- How knowledgeable is your establishment about the process of converting waste cooking oil to biodiesel? (Scale: Not Knowledgeable - Very Knowledgeable)

Attitude

- How important do you think it is to use renewable energy sources like biodiesel? (Scale: Not Important - Very Important)
- Do you believe that using waste cooking oil for biodiesel production is a viable option? (Yes/No)
- How supportive are you of government policies promoting the use of waste cooking oil for biodiesel production? (Scale: Not Supportive - Very Supportive)
- How concerned are you about the potential social impacts of biodiesel on local communities? (Scale: Not Concerned - Very Concerned)

Practice

- How often does your hotel generate waste cooking oil? (Daily, Weekly, Monthly, Less Frequently)
- How does your hotel currently dispose of waste cooking oil? (Disposed as waste, Sold to soap making factories, Sold to biodiesel producers, Other)
- Would your hotel management be willing to provide waste cooking oil to biodiesel producers? (Yes/No)
- How likely is your hotel/restaurant to switch to biodiesel if it were available at a competitive price? (Scale: Not likely - Very likely)

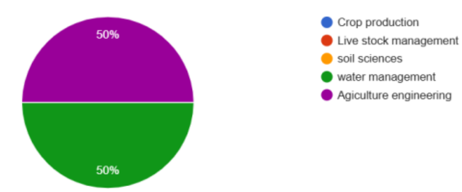
View Point

- Would your management be willing to pay more for biodiesel if it meant supporting sustainable energy? (Yes/No)
- What factors influence your hotel's decision to use or not use biodiesel?
- What challenges does your hotel/restaurant foresee in providing waste cooking oil for biodiesel production?
- What measures would you suggest to improve the collection and utilization of waste cooking oil for biodiesel production?

Responses from Research Institutes

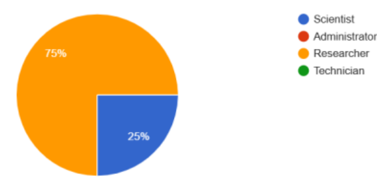
What is the primary focus of your research institute?

4 responses



What is your role in the institute?

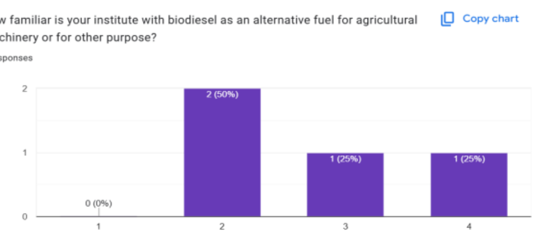
4 responses



Knowledge

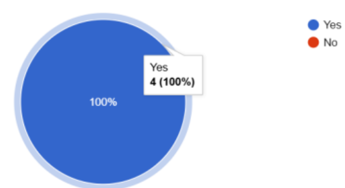
How familiar is your institute with biodiesel as an alternative fuel for agricultural machinery or for other purpose?

4 responses



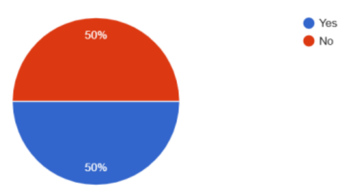
Does your institute know the environmental benefits of using biodiesel compared to conventional diesel in your relevant sector?

4 responses



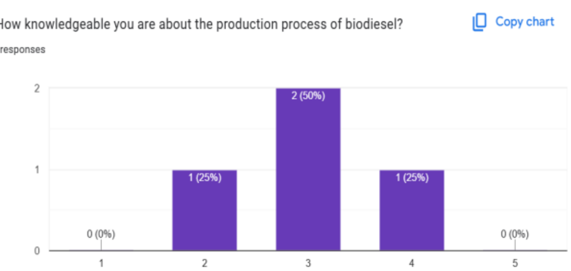
Is your institute aware of the different feedstocks used for biodiesel production?

4 responses



How knowledgeable you are about the production process of biodiesel?

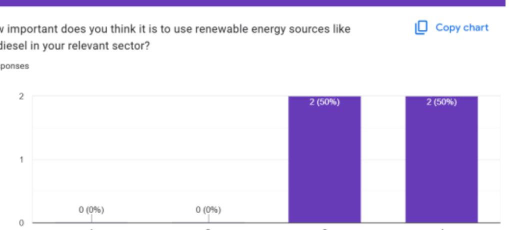
4 responses



Attitude

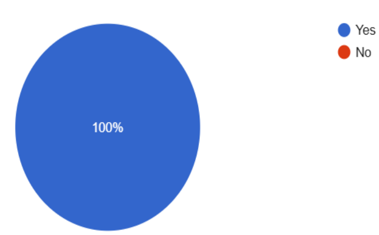
How important does you think it is to use renewable energy sources like biodiesel in your relevant sector?

4 responses



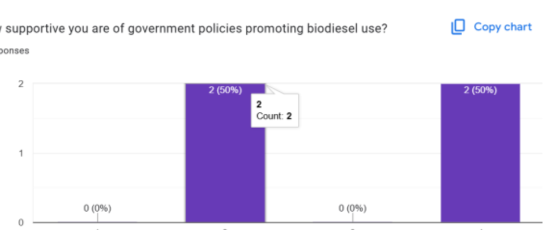
Do you believe that biodiesel is a viable alternative to conventional diesel?

4 responses



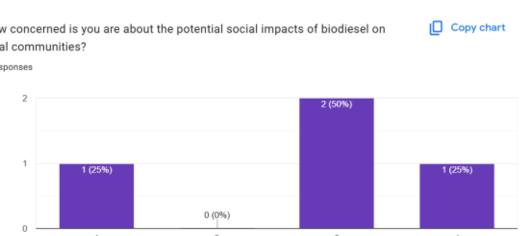
How supportive you are of government policies promoting biodiesel use?

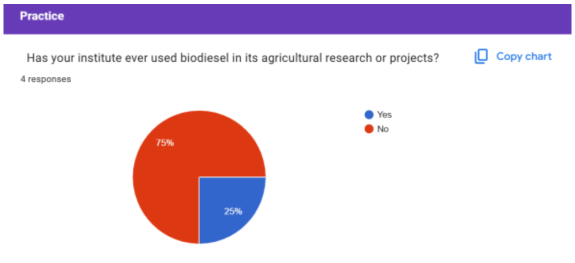
4 responses

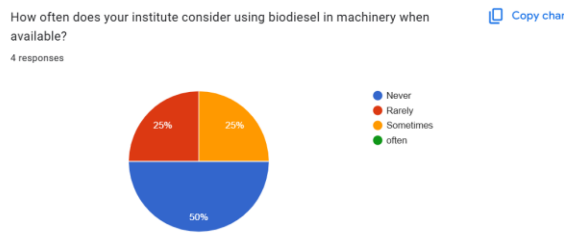


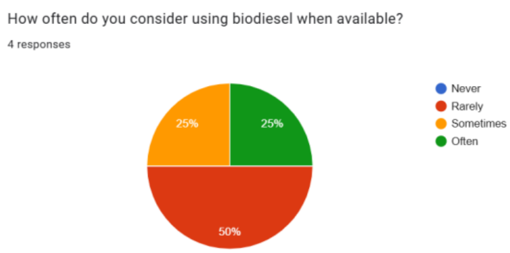
How concerned is you are about the potential social impacts of biodiesel on local communities?

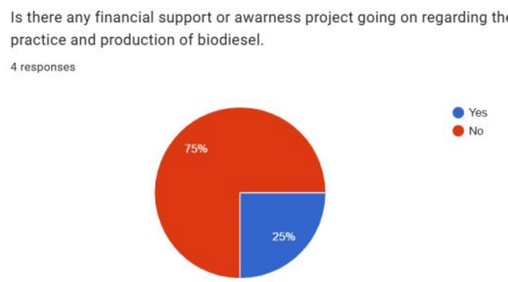
4 responses

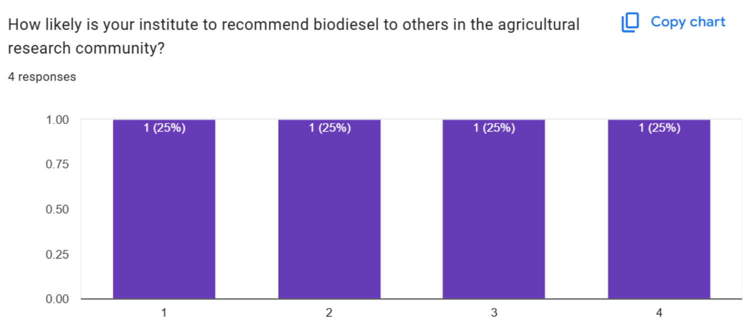




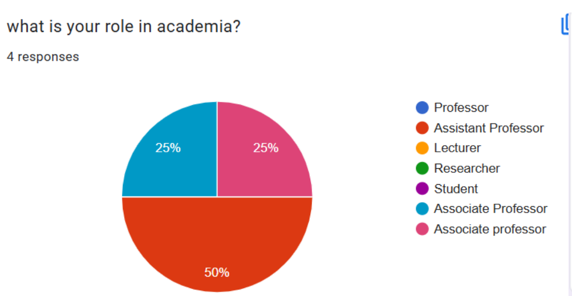


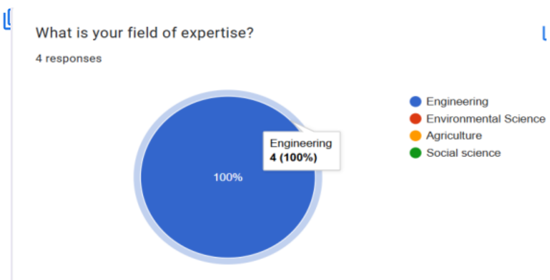






Responses from Academia



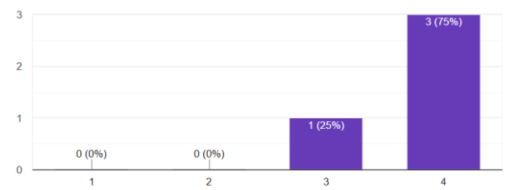


Knowledge

How familiar are you with biodiesel as an alternative fuel?

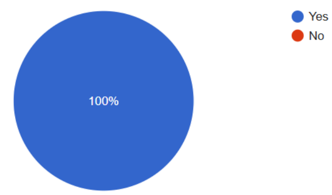
Copy

4 responses



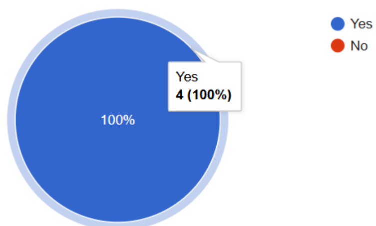
Does you know the environmental benefits of using biodiesel compared to conventional diesel in your relevant sector?

4 responses



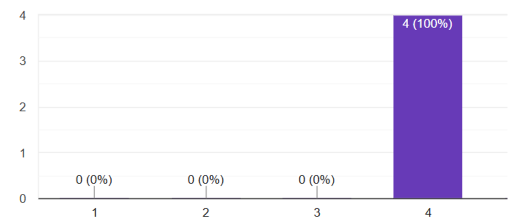
Are you aware of the different feedstocks used for biodiesel production?

4 responses



How knowledgeable you are about the production process of biodiesel?

4 responses

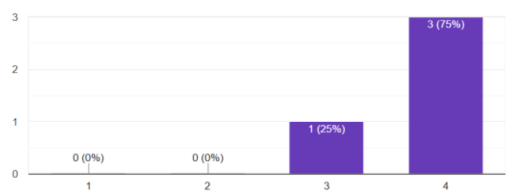


Attitude

How important do you think it is to use renewable energy sources like biodiesel?

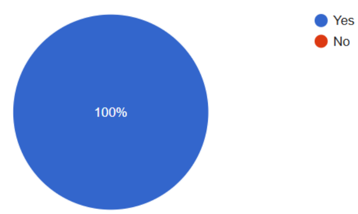
Copy

4 responses



Do you believe that biodiesel is a viable alternative to conventional diesel?

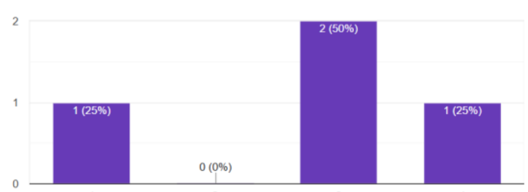
4 responses



How supportive you are of government policies promoting biodiesel use?

Copy

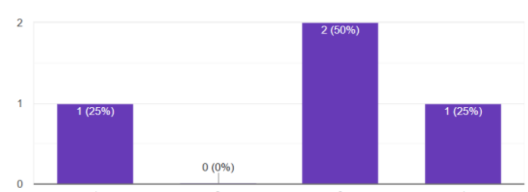
4 responses



How concerned are you are about the potential social impacts of biodiesel on local communities?

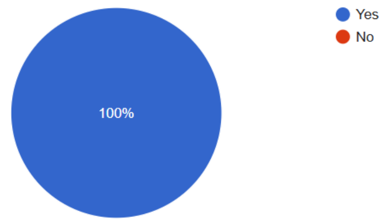
Copy

4 responses



Are you willing for the research on biodiesel in your university?

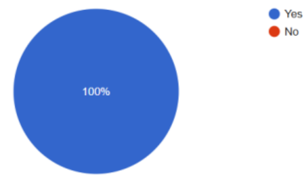
4 responses



Practice

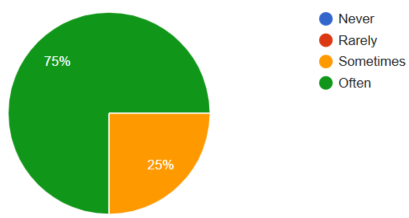
Has your institute ever used biodiesel in research or academic projects?

4 responses



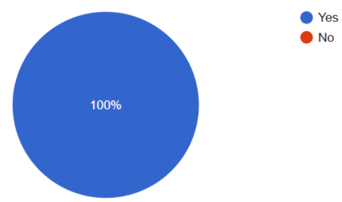
How often do you consider using biodiesel in your academic work when available?

4 responses



Would you be willing for research on biodiesel if it meant supporting sustainable energy?

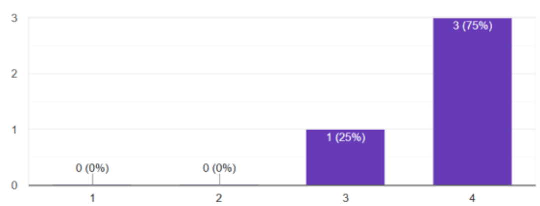
4 responses



How likely are you to recommend biodiesel to others in the academic community?

Copy

4 responses



How likely is your university to recommend biodiesel to others in the community?

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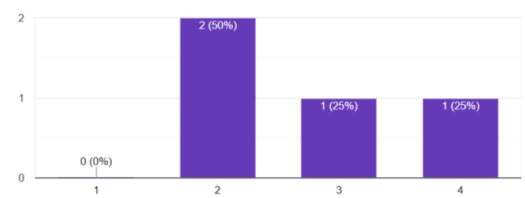
4 responses

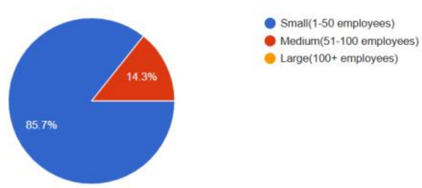


Responses from Industry leaders

What is the size of your company?

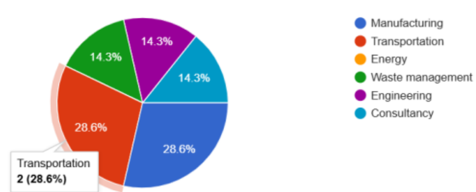
Copy

7 responses



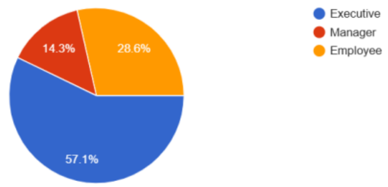
What industry does your company operate in?

7 responses



What is your position in the company?

7 responses

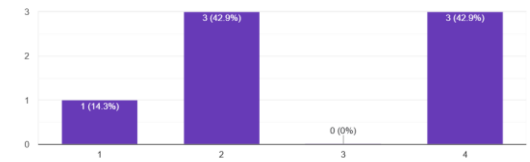


Knowledge

How familiar is your company with biodiesel as an alternative fuel?

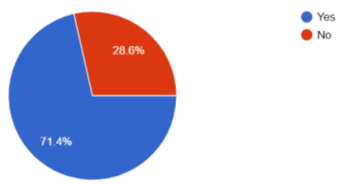
Copy chart

7 responses



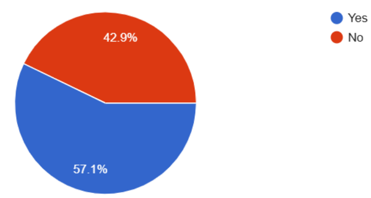
Does your company know the environmental benefits of using biodiesel compared to conventional diesel?

7 responses



Is your company aware of the different feedstocks used for biodiesel production?

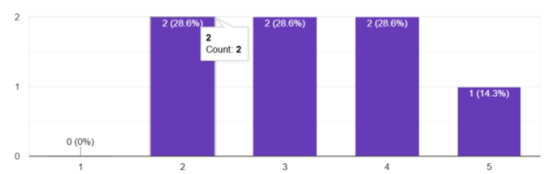
7 responses



How knowledgeable is your company about the production process of biodiesel?

Copy chart

7 responses

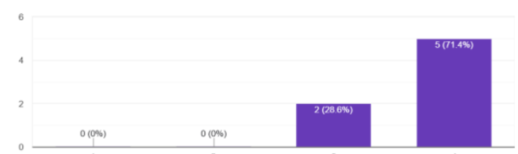


Attitude

How important does your company think it is to use renewable energy sources like biodiesel?

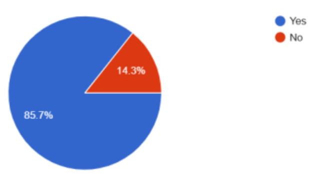
Copy chart

7 responses



Does your company believe that biodiesel is a viable alternative to conventional diesel?

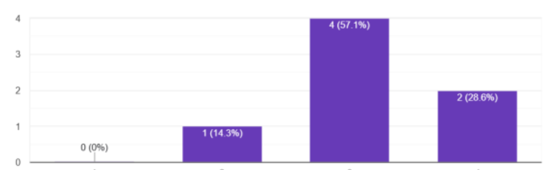
7 responses



How supportive is your company of government policies promoting biodiesel use?

Copy chart

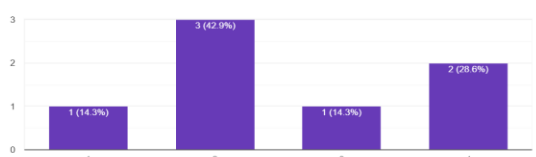
7 responses



How concerned is your company about the potential social impacts of biodiesel on local communities?

Copy chart

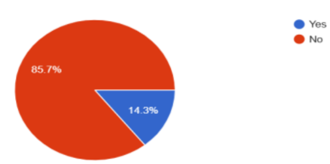
7 responses



Practice

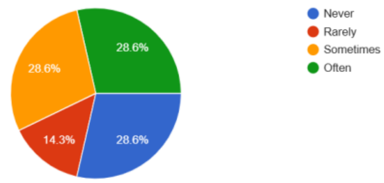
Has your company ever used biodiesel in its operations?

7 responses



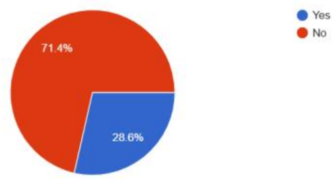
How often does your company consider using biodiesel when available?

7 responses



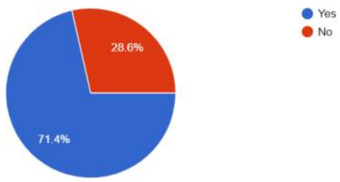
Would your company be willing to pay more for biodiesel if it meant supporting sustainable energy?

7 responses



Would your company be willing to invest in the biodiesel production on pilot scale if it meant supporting sustainable energy?

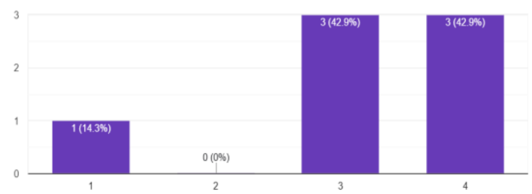
7 responses



How likely is your company to recommend biodiesel to others?

Copy chart

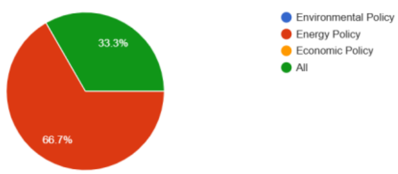
7 responses



Responses from Policy Institutes

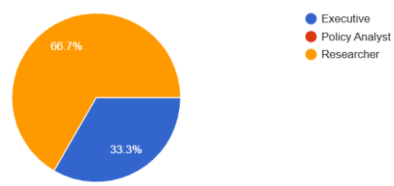
What is the main focus of your policy institute?

3 responses



What is your position in the company?

3 responses

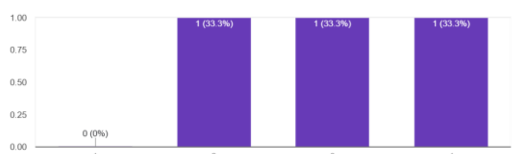


Knowledge

How familiar is your institute with biodiesel as an alternative fuel?

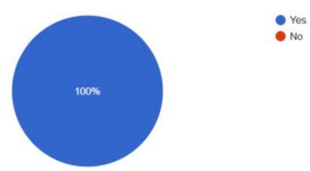
Copy chart

3 responses



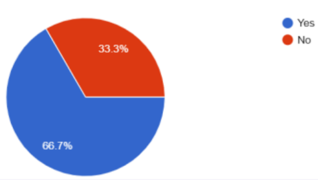
Does your institute know the environmental benefits of using biodiesel compared to conventional diesel?

3 responses



Is your institute aware of the different feedstocks used for biodiesel production?

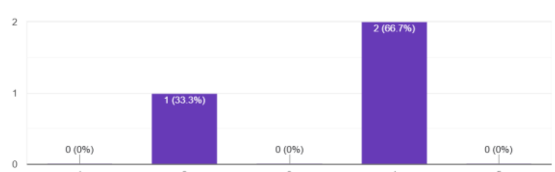
3 responses



How knowledgeable you are about the production process of biodiesel?

Copy chart

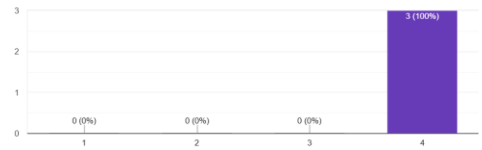
3 responses



Attitude

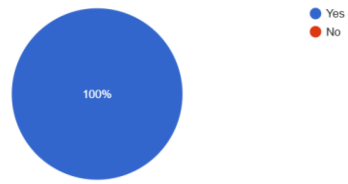
How important do you think it is to use renewable energy sources like biodiesel?

3 responses



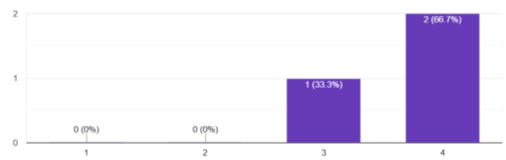
Do you believe that biodiesel is a viable alternative to conventional diesel?

3 responses



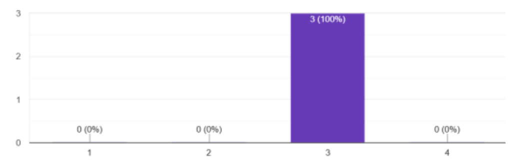
How supportive you are of government policies promoting biodiesel use?

3 responses



How concerned you are about the potential social impacts of biodiesel on local communities?

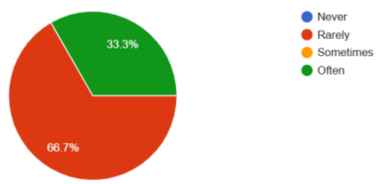
3 responses



Practice

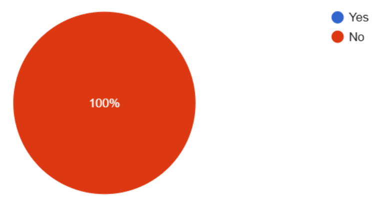
How often do you consider using biodiesel when available?

3 responses



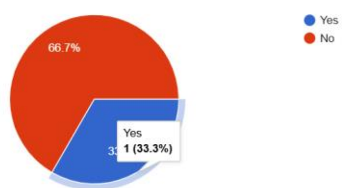
Is there any financial support or awarness project going on regarding the practice and production of biodiesel.

3 responses



Are you aware of any policy about biodiesel or govt initiative to develop policy for biodiesel program?

3 responses



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[1] A. Olhoff *et al.*, *Emissions Gap Report 2024: No more hot air … please! With a massive gap between rhetoric and reality, countries draft new climate commitments*. United Nations Environment Programme, 2024. doi: 10.59117/20.500.11822/46404.

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