CONVERSION OF WASTE COOKING OIL INTO BIODIESEL BY TRANSESTERIFICATION REACTION

A THESIS

Submitted Towards the requirement for the Award of degree of

Doctor of Philosophy

In

DEPARTMENT OF BIOTECHNOLGY

Under the Faculty of Science

By

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Under the Supervision of

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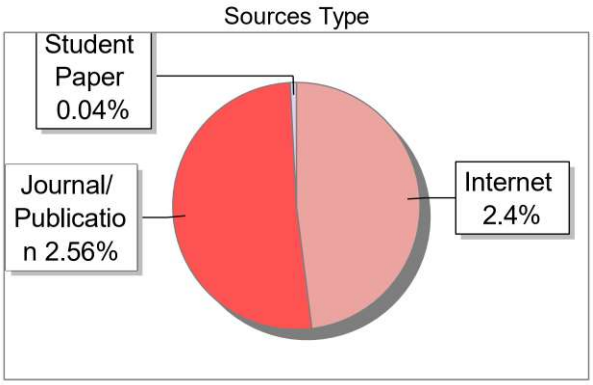
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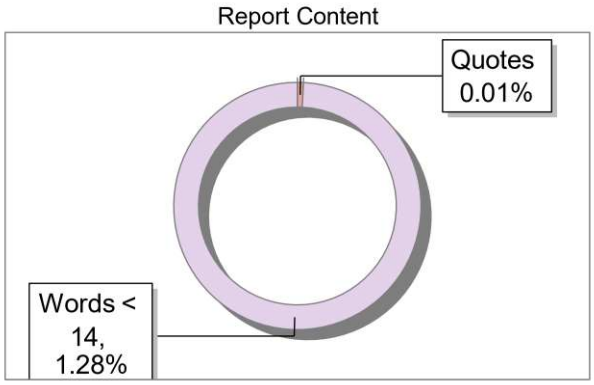
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ABSTRACT

The transesterification reaction, which converts waste cooking oil into biodiesel, is a novel and practical approach to addressing energy and environmental issues. The goal of this study was to prepare and characterize a zinc-doped calcium oxide (Zn-CaO) catalyst for the wet impregnation method of making biodiesel from used cooking oil. To produce biodiesel, the obtained catalyst was used in a transesterification reaction with methanol. The results of these tests will be used to determine the effectivity of using biodiesel as an alternative fuel. The purpose of this study is to aid in the evaluation of biodiesel in terms of environmental sustainability as well as the development of environmentally friendly and efficient biodiesel production methods. The idea of a circular economy, in which waste products are turned into useful resources, is supported by the utilization of used cooking oil.

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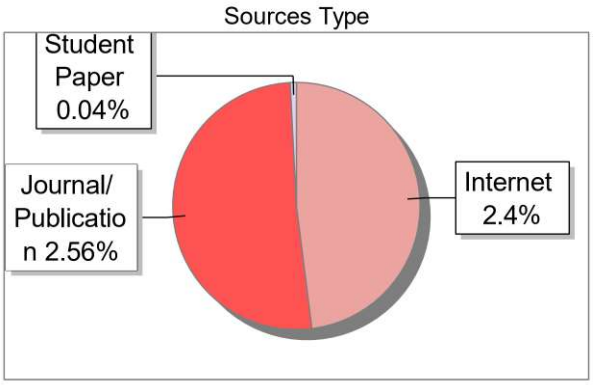
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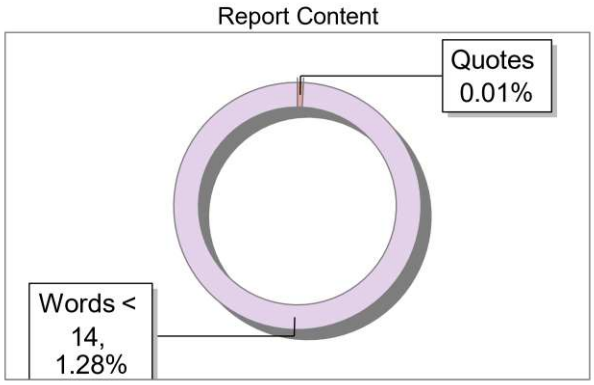
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ABSTRACT

The transesterification reaction, which converts waste cooking oil into biodiesel, is a novel and practical approach to addressing energy and environmental issues. The goal of this study was to prepare and characterize a zinc-doped calcium oxide (Zn-CaO) catalyst for the wet impregnation method of making biodiesel from used cooking oil. To produce biodiesel, the obtained catalyst was used in a transesterification reaction with methanol. The results of these tests will be used to determine the effectivity of using biodiesel as an alternative fuel. The purpose of this study is to aid in the evaluation of biodiesel in terms of environmental sustainability as well as the development of environmentally friendly and efficient biodiesel production methods. The idea of a circular economy, in which waste products are turned into useful resources, is supported by the utilization of used cooking oil.

INTRODUCTION

The conversion of waste cooking oil (WCO) into biological diesel thanks to the transesterification reaction is a profitable method and respect the recycling of waste oil into useful fuel. With increasing concerns about the exhaustion of fossil fuels, greenhouse gas emissions and environmental pollution, bio-production from WCO is a feasible and green solution for these problems [1]. The removal of used oils is a serious environmental threat to water pollution, soil pollution and more waste in landfills. Instead of having a WCO, turning it into a biological diesel has a double advantage it not only reduces the harmful environmental impact of inaccurate removal, but also helps create renewable energy. By minimizing waste and optimizing resource utilization, the use of WCO in the production of biological diesel encourages the transition to renewable energy and the principles of the circulating economy.

The transesterification reaction, a chemical reaction that converts triglycerides the primary constituents of WCO into either ethyl ester D 'Gras, which is biological diesel, or methyl fat of fatty acids, which is well-known, is at the centre of the process of producing biological diesel from WCO. Another by-product of this reaction is glycerol, which can be processed and applied in a variety of fields, including food processing, cosmetics, and pharmaceuticals. When a catalyst is available, transesterification refers to the breakdown of waste molecules from triglycerides into lower molecular ester compounds through alcohol-related processes like methanol or ethanol. The catalyst facilitates the efficient conversion of WCO to biological diesel by accelerating the reaction. The use of suitable catalysts will speed up the reaction by permitting ester separation and producing high biological diesel productivity since neutral fat is hydrophobic and resists direct transformation.

The viability and effectiveness of the transesterification process are significantly impacted by the choice of catalyst. The most widely employed catalysts for WCO-based biodiesel synthesis are alkaline (base) catalysts, such as potassium hydroxide (KOH) and sodium hydroxide (NaOH), due to their high reactivity, which permits a rapid rate of reaction at mild operating conditions. Acid catalysts, e.g., sulfuric acid (H_2SO_4), can also be applied when the WCO has high free fatty acids (FFAs) content, which may cause soap formation and decrease the yield of biodiesel in base-catalyzed reactions [2]. On certain occasions, enzymatic catalysts have been looked into as an environmentally friendly substitute, providing high selectivity and efficiency

of conversion with low side reactions, though with longer reaction times and added expense than for traditional chemical catalysts.

One of the major benefits of employing WCO as a raw material for biodiesel production lies in its cost-effectiveness. As WCO is an easily accessible waste product, especially from restaurants, food processing plants, and homes, utilizing it as a raw material lowers the cost of production dramatically as compared to biodiesel from virgin vegetable oils. This cost-effectiveness renders WCO biodiesel a very promising alternative fuel source, especially where waste oil collection infrastructure is highly developed. In addition, WCO redirects to use as raw materials of biological diesel to help sustainable by minimizing the environmental impact of removal of waste while helping energy security and reducing fuel dependence. Traditional materials.

The effect of transesterification reactions in biological diesel quality is affected by different important parameters, such as reaction temperature, oil ratio of oil in oil, concentration of catalysts and reaction time. The optimization of these variables ensures that biological diesel is obtained in accordance with the industry's specifications related to fuel properties such as viscosity, cetane quantity, density and flash points. These features are of the main importance to ensure the compatibility with conventional diesel engines, enhance the effectiveness of the burning process and reduce emissions [3]. By selecting an appropriate catalyst and correct adjustment of reaction conditions, biological diesel -based diesel conditions can provide high -quality and high quality, an interesting replacement for fossil fuel like a renewable resource. The last, the transesterification of WCO into a biological diesel provides an evolutionary and feasible means to produce sustainable energy. Using waste oil as a raw material can regenerate, this process not only presents an ecological waste management method, but also promotes the global transition to cleaner and more durable fuel sources. With continuous improvements in biological diesel production technology, Transesterification technology continues to take the lead in the breakthroughs of renewable energy, instructing the path to an effective and durable fuel economy.

1.1. BACKGROUND AND MOTIVATION

Growing Demand for Alternative Energy Sources

The global energy scenario faces a change in the sea due to an increasing alarm compared to climate change, the decline in fossil fuel resources and ecological costs of traditional energy sources. For more than a century, coal, oil and natural gas are growing engine and industrial

mobile. But their endless exploitation has led to serious environmental and geopolitical problems. The production, processing and burning of fossil fuels emit tons of greenhouse gases (GHG), especially (CO_2), this is the main cause of global warming and uncertainty about gas. This requires the need for large, cleaner and durable energy sources. In addition, air pollution due to the process of burning fossil fuel has serious consequences for health, especially respiratory diseases, cardiovascular disease and early death, especially in the urban area. have high population density [4]. With an increase in global demand for population and energy, this environmental and health issue has become a priority for decisions, researchers and industry decided.

Increasing consciousness of the limitations of fossil fuel has further stimulated the transition to replacement energy sources. Fuel reserves have been exhausted at a very fast speed, leading to price fluctuations and geopolitical tensions. In addition to unexpected energy countries that are vulnerable to dietary problems and economic uncertainties, the majority of oil producing nations have a major influence on the global fuel supply chain. Countries are looking for independent and sustainable energy sources to reduce their reliance on imported fossil fuels as a result of the growing need for energy safety. Investments in renewable energy infrastructure, including wind turbines, solar power, hydroelectricity, and biotechnology, have increased as a result. Of these, biological energy has increased significant interest because it has the ability to provide a neutral carbon replacement and regenerate fossil fuel. Biofuel such as biology and biological diesel is made up of organic resources and provides an environmentally friendly means to combat the energy crisis, in addition to resolving green concerns.

The conversion to replacement energy resources is mainly motivated by three factors: climate change, improving energy security and gaining economic benefits from renewable energy technologies. The decline in climate change is always the main goal, countries around the world seek to reduce carbon levels according to international goals under agreements such as Paris climate agreement. The transportation field, for example, is one of the largest carbon emissions in the world, calling for measures to immediately apply greener fuel options. Biological diesel, green fuel made from vegetable oil, animal fat and waste cooking oil (WCO), have become popular as a feasible option depending on the decreasing carbon footprints and compatibility of It is with normal diesel fuel engine with little or no modification. Unlike fossil fuel, underground carbon for millions of years, biological diesel is neutral carbon like carbon dioxide released when combined with carbon absorbed by food factories in their cycle growth process.

As well as environmental impacts, the process of conversion to renewable energy, especially biofuel, has significant economic advantages. Biological diesel production creates local employment capabilities, supports the rural economy and provides energy itself. Governments around the world have provided political interventions such as tax reduction, allowance and renewable energy standards to promote the use of biological diesel. Such initiatives have significantly accelerated research and innovation of biofuel technologies, leading to higher production efficiency, reducing costs and fuel quality [5]. In addition, the use of waste lines such as WCO as raw materials to synthesize biological diesel is a circulating economic form, eliminating the creation of waste and producing high quality fuel. This sustainable approach aligns with global goals to lessen reliance on fossil fuels and to design more stable and clean energy infrastructure.

Biodiversity diesel has emerged as a significant player in the renewable energy sector as the world's energy demands continue to rise. The significance of biological diesel in difficult circumstances is highlighted by the fact that the development of biofuel technology and government regulations promoting the use of renewable energy sources have resulted in the requirement for cleaner fuel. About today's energy. Countries can significantly reduce their environmental footprints while simultaneously providing a safe and diverse energy supply for future generations by incorporating biological diesel into existing fuel systems.

Increasing Attention on Biodiesel

Biological diesel is widely acknowledged as an effective alternative to conventional diesel engines because it is a clean, rebuilt fuel. It is mostly made of a variety of organic raw materials, like vegetable oil, animal fat, and waste cooking oil (WCO). Because biological diesel might lower emissions of harmful pollutants and greenhouse gases (GHG), the primary cause of air pollution and climate change, interest in it is growing. Biological diesel is a cleaner and greener alternative to petroleum diesel engines, which release a lot of (CO_2), (NOx), and sulfur compounds and particulates when they burn. Biological diesel is marketed as a transportation, industrial, and energy production alternative in response to concerns about the depletion of fossil fuels and health hazards resulting from pollution.

The fact that biological diesel is carbon neutral is one of its most significant environmental benefits over conventional diesel. Biological diesel works in a closed carbon cycle, whereas fossil fuel is carbon that has been buried underground for millions of years. CO_2 emitted during the biological diesel burning process is balanced by carbon performed by vegetation used as

raw materials in their growth cycle [6]. This mechanism has the actual effectiveness of biological diesel for the amount of CO_2 in the atmosphere, reducing the overall emissions of greenhouse gases. This quality completes international efforts to prevent climate change and complement the global mechanisms such as Paris agreement, designed to limit the global temperature in the temperature increased by dependence on these dependences. The energy source of heavy carbon. Therefore, the use of biological diesel creates an important evolution for a cheap economy, reducing the environmental impact of transport and industrial fields.

Aside from its environmental advantages, biodiesel is also non-toxic and biodegradable, minimizing the possibility of contaminating the environment in case of leaks or spills. In contrast to petroleum-derived fuels, which may lead to long-term ecological harm when spilled, biodiesel naturally degrades and does not pose significant harm to water bodies, soil, and aquatic life. This attribute renders biodiesel a cleaner alternative, especially in sectors like shipping and agriculture, where fuel spills present an environmental nightmare. Additionally, the low Sulfur content in biodiesel leads to fewer acid rain formations and less corrosion risk in fuel distribution and storage networks, making it even more environmentally friendly.

Another significant advantage of biological diesel is that it can be made from a variety of raw materials, from virgin pure oil (for example, soybeans, brushes and canola) to animal fat and waste. Cook oil. The flexibility of this raw material makes the production process more flexible and decentralized, allowing the production of biological diesel to be optimized in local agricultural conditions and the available resources. The use of non-quality waste and raw materials also facilitates food security issues, because it reduces the competition between fuel production and food. In addition, the ability to use waste oil to produce biological diesel promotes the circulating economic model eliminating the problems of eliminating waste while providing another source of income for industries and households. oil production used.

Increasing demand for biological diesel is also supported by government incentives and policies to apply renewable energy. Most countries have established biological diesel, tax and allowances requirements to promote consumption and production [7]. For example, biological diesel is widely mixed with diesel oil in different reports (for example, B5, B20 and B100), allowing smooth changes for cleaner fuel without large changes in the cave. Current diesel. In addition, the development in biological diesel production technologies, including trans ester and catalytic technologies improved, improved the quality, efficiency and fuel's ability to pay, created out a more feasible biological diesel in the international energy market.

With concerns about energy security, environmental sustainability and climate change day by day, biological diesel has become an important player in the renewable energy space. With the potential for reducing emissions, encouraging energy independence and ensuring economic advantages by using sustainable raw materials, it becomes an important factor in future energy policies. The integration of biological diesel into conventional fuel infrastructure allows countries to become independent of fossil fuels while shaping a greener and safer future.

1.2. WASTE COOKING OIL (WCO) AS A FEEDSTOCK

Waste cooking oil (WCO) is a by -products formed during cooking, often used to prepare food, fry or other cooking activities at high temperatures. With the world planning to replace fossil fuels and by reducing environmental pollution, WCO has become a valid and feasible raw material to produce biological diesel oil. The process of converting the biological WCO diesel is not only a way to remove waste, but also an environmentally friendly fuel replacement that supports sustainable use of energy.



Figure: 1.1.- Waste Cooking Oil (WCO)

1.2.1 Sources of WCO

Cooking Waste Used cooking oil is oil that has been thermally degraded during food preparation. Animal fats like lard or tallow, or vegetable fats like soybean, sunflower, canola, and palm oils, are the most prevalent sources [8]. WCO is produced after oils are heated to

high temperatures, altering their chemical makeup and producing substances such carbon residues, oxidized products, and free fatty acids. The oil thus becomes inappropriate for more cooking purposes but remains rich in valuable constituents that can be recovered into biodiesel. Sources of WCO are:

- **Households:** Domestic kitchens in which cooking oils are heated for frying or deep-frying.
- **Restaurants and Food Chains:** Institutional food outlets that frequently employ vast amounts of oil for deep-frying and other cooking operations.
- **Catering Services and street vendors:** Big caterers or food processing facilities where large volumes of oil are utilized in the manufacture of ready-to-eat meals.

WCO may be of domestic or industrial origin, and its presence is an environmental problem, particularly if it is not disposed of appropriately.

1.2.2 Importance of WCO in the Context of Sustainability

Waste Cooking Oil has attracted considerable interest in the sustainability context due to the fact that it provides a cheap and plentiful feedstock for the production of biodiesel. Biodiesel is a renewable fuel, and the utilization of WCO helps to decrease dependence on virgin oils, which are extracted from food crops such as soybeans or palm trees, frequently associated with deforestation and land use issues.

The abundance and accessibility

WCO is produced daily in the amount nourished by households, restaurants and food processing industry around the world. This wide supply makes WCO a feasible and coherent raw material for biological diesel production, so a practical reaction to the increase of global energy demand. The collection of used oils is promoted in most regions in the world as a method of reducing waste, providing power sources for biological diesel manufacturers.

Lower cost than pure oil

one of the main advantages of using WCO as raw materials to produce biological diesel is relatively low cost. Waste oil is much cheaper than pure oil, and therefore, the production of bio -diesel oil from WCO is economically possible [9]. In most cases, waste oil is taken free or with very little costs of restaurants and food transformers, making it cheaper for the cost of producing general biological diesel and increasing competitiveness against resistance.

Fossil fuel

Biodiesel made from used cooking oil is considered carbon-neutral because the carbon dioxide released during combustion is balanced by the carbon that was stored in the plants as they developed.

1.2.3 Environmental Concerns Related to Improper Disposal of WCO

Waste cooking oil (WCO) improper disposal is a major environmental problem that has an extensive effect on land, water, air quality, and human health. WCO is created in large quantities by homes, eateries, and food processing businesses, and it can seriously harm the environment if not disposed of properly. Numerous individuals and organizations dispose of waste cooking oil by flushing it down drains, sinks, or onto the ground directly, with some pouring it in landfills as other wastes. These disposal methods, though prevalent, may result in permanent damage to ecosystems, water bodies, and urban systems. Due to the global rising demand for fried and processed food, finding a solution to WCO disposal is paramount in promoting environmental sustainability.

1. **Water Pollution and Its Consequences**

One of the most critical environmental concerns related to WCO disposal is water pollution. Cooking oil is used to be washed when drainage or sewers finally find their way in urban wastewater systems and, in most cases, on rivers, lakes and oceans. WCO is hydrophobic and does not mix with water but creates a thick membrane on the surface of the water. This layer prevents oxygen exchange between water and air, significantly damaging underwater ecosystems. Low oxygen concentration (oxygen deficiency) can clog fish, underwater life and other marine life, destroy adequate food chains. Oil in waters can change the pH level and turbidity of the water, which makes it less friendly to the aquatic life. In addition, WCO tends to have food waste, additives and broken petroleum products that can place toxic substances in the water supply. These pollutants can be heavy metals, polycyclic aromatic hydrocarbons (PAHs) and trans-fat, toxic to aquatic and humans. WCO -contaminated waters can also promote the over crow ness of toxic bacteria, causing a decrease in water quality. The pollution of water sources due to WCO pollution is a serious community health risk, which can cause gastrointestinal diseases and other health problems in the community depending on water sources unreasonable treatment [10].

2. Soil Pollution and Long-Term Degradation

Incorrect dumping of WCO on land or blending it into soil causes soil pollution on a large scale. When oil penetrates the ground, it creates a thick hydrophobic layer that destroys the structure of the soil and prevents water percolation. The process hinders the soil's moisture retention capacity, affecting plant growth and resulting in soil infertility after a while. WCO in the soil also eliminates normal decomposition activity performed by bacteria, soil quality decomposition and its ability to produce in agriculture. In addition, WCO can also transport chemical residues from the cooking process, such as cancer-causing chemicals that are still in the soil and are able to filter in underground water resources. The soil polluted by oil can be dangerous to food crops, because plants absorb these harmful chemicals, thus transmitting them to human food chains. In urban areas, land polluted by oil can hinder the drainage pipes and cause local floods in rain storms, increasing infrastructure and hygienic problems.

3. Odor Issues and Attraction of Pests

WCO is removed in public spaces, waste or waste tanks that can create unpleasant odors, which has increased environmental and hygienic problems. Because oil decomposition is aging, volatile organic compounds (VOC) are issued, not only causes unpleasant odors, but also has the potential to pollute the air and respiratory disease in humans. The Putrid smell of rotten oils is particularly ashamed of in urban areas where the population density sets an intense fee for the infrastructure to remove waste.

In addition, the removal of WCO may not be suitable for rodents like rats, cockroaches and flies. These rodents prefer organic waste to survive, and the existence of WCO among the piles of waste or drainage can cause us to amplify. A large number of current harmful species have a serious concern for public health, because these people can transmit Leptospirosis, Salmonella and other bacterial diseases. In the food preparation, the penetration of harmful species related to the removal of the WCO can weaken the level of hygiene and attract compliance with regulations, leading to financial losses. Business and may have risks for health consumers.

4. Waste Management Challenges and Infrastructure Strain

The build-up of WCO in landfills and wastewater treatment plants contributes to the load on already strained waste management systems. Most municipal treatment plants lack the capability to handle massive amounts of WCO, which creates inefficiencies in the waste disposal process. When WCO finds its way into sewer systems, it mixes with other trash and

solid waste to create "fatbergs"—giant, solid chunks of grease and fat that clog pipes and sewer systems. Such blockages may lead to sewer overflows, contaminating the environment, incurring expensive maintenance services, and interference with public sanitation services [11].

Moreover, landfilling WCO is not a long-term solution, as oil is not biodegradable and will remain in the environment for a long time. The long -term WCO storage during the discharge increases the risk of leachate formation - where dangerous chemicals enter the soil and groundwater and create threats to the surrounding communities. Useless WCO management also leads to wasting valuable resources; Instead of being thrown away, WCO can be restored and converted into bio -diesel oil, this is a cleaner and greener fuel option.

1.2.4 Role of WCO in the Circular Economy

circulating economy is an environmentally friendly economic model for the purpose of reducing waste by recycling and reusing materials and introducing them to the round. manufacture. Unlike the usual linear economy, tend to "take, do, handle", the circulating economy sought to close resources of resources by activities such as recycling, reusing and Reuse waste. WCO is very important in this system by converting into waste with a product into a useful energy source - biological diesel. This not only helps manage waste, but also energy sustainability and environmental conservation.

1. **Repurposing Waste for New Use**

One of the main principles of the circulating economy is to make the most of the materials before being thrown. WCO, often considered waste, can be used to produce biological diesel oil and thus expand its application beyond the original goal. Instead of going to waste or drainage system where it has a devastating environment WCO is collected and used as a pure and durable fuel source.

WCO is transformed into biological diesel using a chemical process known as transesterification, which combines oil with alcohol (often methanol or ethanol) in the presence of a catalyst to create glycerol and biological diesel is a by-product. Biological diesel produced can be used in different applications, including transportation, heating and energy production, such as a green replacement for traditional fossil fuel. The recycling of this waste promotes the principle of reduction, reuse and recycling which are the main principles of the circulating economy [12].

2. Closing the Loop in Waste Management and Energy Production

In a circulating economy, the goal is to make the materials as long as possible before being recycled or reused. The use of WCO in biological diesel is a way that waste can be restored transparently in the economy and not an environmental cost. When households and industries provide their waste oil to purify biological diesel, they help close the waste loop by recycling unwanted waste in renewable energy.

This practice minimizes not only the amount of waste in discharging and wastewater treatment plants, but also reduces dependence on pure oils, soil and giant water to produce. In addition, the use of WCO biological diesel has minimized fossil fuel consumption, reduces greenhouse gas emissions and promotes cleaner energy -alternative options. The integration of WCO into energy systems is a perfect example of waste converted into a valuable resource, showing more emphasis on the circulating economy of sustainability and efficiency of resources.

3. Economic and Environmental Advantages

WCO function in the circulating economy are not only manipulation of waste and energy production - it also has economic and environmental value. Producing biological diesel focuses on WCO provides jobs in areas such as waste collection, oil treatment and fuel supply. WCO can be collected and treated by local businesses and small businesses, providing economic opportunities as well as jobs that promote greener approach to development.

From the ecological point of view, the manufacture of biological diesel utilizing WCO as a raw material that minimizes carbon footprints compared to traditional diesel engines. WCO Bio Diesel is less than a carbon creation technique because it reshapes the waste in contrast to the elimination of new environmental resources. In addition, because the biological diesel is cleaner than the oil fuel, it helps minimize other air pollutants such as sulfur oxide (SOx), (NOx) and particulates. This biofuel conversion process produces cleaner air, lower greenhouse gasses and greener fuel efficient.

In addition, the full operation of the WCO avoids environmental risks accompanied by inappropriate removal, especially water pollution and soil degradation. The entertainment of used cooking oil of drainage and discharge systems reduces the possibility of blocked drainage systems, the destruction of pests and odour pollution. The economic and environmental advantages of WCO recycling illustrate the ability to help sustainable development as well as cleaner and more effective energy industry [13].

4. Local Recycling Initiatives and Community Engagement

Many organizations and communities have seen the importance of WCO recycling and have established collection programs to ensure good removal and reuse. These programs promote households, restaurants and food facilities to provide used oil for biological diesel production facilities, by supporting local sustainable activities. Some cities even have special deposits for WCO, so it is collected and used in a responsible way instead of being thrown into the environment in unwanted ways.

local recycling initiatives also play an important role in improving community awareness for sustainability and responsible waste removal. Thanks to the public education and businesses about the negative effects of the WCO elimination inaccurate and the advantages of biological diesel production, these programs lead to higher awareness of the environment and habits. More sustainable consumption. In addition, recycling programs based on the district can provide income participants by providing cash incentives or payment to used donations, once again supporting feasibility.

1.3. BIODIESEL AS AN ALTERNATIVE FUEL FROM WCO

The world tending towards sustainable energy solutions, biodiesel has become a prominent option as an alternative to fossil fuels. Biodiesel, dominated by Fatty Acid Methyl Esters (FAMEs), is a biodegradable, renewable fuel made from biological materials l ike vegetable oils, animal fat, and waste cooking oil (WCO). Its potential to curtail greenhouse gas emissions, improve energy security, and use waste products makes it an attractive option in countering climate change and degradation of the environment.

This section gives a complete overview of biodiesel, including its definition, feedstock-based classification, general chemical composition, and detailed description of the components present in waste cooking oil (WCO), vegetable oil-based biodiesel, and animal fat-based biodiesel. It also describes how WCO is classified according to its usage lifecycle [21].

1.3.1 Components in Waste Cooking Oil (WCO)

Waste Cooking Oil (WCO) is produced when edible oils are fried repeatedly as well as used for other high-temperature cooking operations. Its chemical composition changes substantially because of thermal degradation, oxidation, and contamination during frying.

❖ **Key components in WCO include**

1. **Partially Degraded Triglycerides:** Waste cooking oil (WCO) has oxidized and polymerized triglycerides because of frequent exposure to high temperatures under cooking conditions. These degraded molecules lower the efficacy of the transesterification reaction and may cause lower biodiesel yield unless they are subjected to proper processing.

2. **Free Fatty Acids (FFAs):** Thermal decomposition of triglycerides on extended frying leads to a rise in free fatty acid (FFA) content. Excessive amounts of FFAs increase the acidity of WCO, which may lead to soap formation during biodiesel processing if not pre-treated by acid esterification or neutralization.

3. **Peroxides and Aldehydes:** Repeated heating and oxidation of cooking oil form peroxides and aldehydes, which are toxic degradation products. These molecules not only reduce the oxidative stability of biodiesel but also influence the storage life and combustion properties of the fuel if left behind.

4. **Food Residues and Carbon Particles:** Solid food residues and carbon particles suspended in the oil during frying. These must be removed in the pre-treatment process, as they will disrupt reaction efficiency and contaminate the resultant biodiesel.

5. **Water and Moisture:** WCO tends to have high levels of water and moisture resulting from the cooking process and food absorption. High moisture levels are known to result in hydrolysis of triglycerides, which increases the formation of FFAs and reduces biodiesel yield, in addition to supporting microbial growth on storage.

6. **Colour and Odor Compounds:** When subjected to repeated heating, the oil turns dark in colour and possesses obnoxious odour as a result of formation of volatile degrading compounds. Aesthetic appearance resulting from such changes is a demonstration of chemical degradability, which could find expression on final biodiesel in terms of acceptance and quality, unless redressed during the course of refining [22].

Being composition-variable, WCO requires a certain pre-treatment (e.g., filtering, dewatering, neutralisation) before employment in biodiesel production.

1.3.2 Definition and Types of Biodiesel (FAMEs)

Biodiesel is a clean-burning replacement fuel made of mono-alkyl esters of long-chain fatty acids of renewable lipid origin. Production happens through transesterification when

triglycerides (oils and fats) are mixed with a short-chain alcohol (generally methanol) and catalyst (like sodium or potassium hydroxide) to produce Fatty Acid Methyl Esters (FAMEs) and glycerol.

The resulting FAMEs are Petro diesel-like in their properties, so biodiesel can be used in current diesel engines and infrastructure without major modifications.

❖ **Types of Biodiesels Based on Feedstock**

- **Vegetable Oil-Based Biodiesel**: Obtained from edible and non-edible oils like soybean, canola, sunflower, and palm oil. These oils contain high triglyceride content and are commonly used because they are readily available and have relatively low free fatty acid content.
- **Animal Fat-Based Biodiesel**: Obtained from animal fat rendering, like tallow, lard, and chicken fat. They contain high concentrations of saturated fatty acids, which are beneficial in increasing oxidative stability but may affect cold flow properties.
- **Waste Oil-Based Biodiesel (WCO)**: From used cooking oil gathered from local homes, eateries, and industrial kitchens. WCO is a cost-saving and environmentally friendly alternative that aids in waste management and conservation of the environment.

1.3.3 General Chemical Components in Biodiesel

The chemical makeup of biodiesel is dependent on the feedstock and method of production. A number of central components are, however, present in all FAME-based biodiesel:

1. **Methyl Esters of Fatty Acids**: Methyl esters, formed in the transesterification reaction, constitute the main energy-carrying compounds in biodiesel. Methyl esters determine critical fuel characteristics like viscosity, cetane number or ignition quality, and oxidative stability, which in turn affect engine efficiency, combustion performance, and storage life of the fuel.
2. **Residual Alcohol**: Small amounts of unreacted methanol or ethanol can remain in the final biodiesel product if not removed properly. Free alcohol can lead to corrosion in engine parts and storage tanks, lower fuel lubricity, and add to incomplete combustion, thus making complete removal during purification essential.
3. **Glycerol**: Glycerol is a natural transesterification by-product and must be effectively removed from biodiesel to prevent contamination. The presence of glycerol in the end

product reduces quality specifications, raises viscosity, and may plug engine filters, highlight the importance of good phase separation and wash processes.

4. **Free Fatty Acids (FFAs)**: Elevated FFA content in feedstock oils causes undesirable soap formation when they react with alkaline catalysts, lowering biodiesel yield and making purification more difficult. Hence, feedstocks containing high FFAs are pre-treated by acid esterification or processed cautiously to preserve product quality.

5. **Water Content**: Water contamination in biodiesel can encourage microbial growth, fuel degradation, and corrosion of storage tanks and engine components. Very low moisture content through proper drying is necessary to ensure fuel stability, performance, and durability.

6. **Catalyst Residues**: During production, catalyst residues such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) can be left suspended in the biodiesel. Left untreated by washing and filtration, these residues have the potential to create engine deposits, impact combustion, and impair overall fuel quality.

Components in Vegetable Oil-Based Biodiesel

Vegetable oil feedstocks, such as those from soybean, canola, and palm, are high in unsaturated fatty acids. Their FAME profiles generally contain:

- **Oleic Acid (C18:1) –** Enhances cold flow properties and oxidative stability.
- **Linoleic Acid (C18:2)** – Improves ignition quality but may reduce oxidative stability.
- **Palmitic Acid (C16:0) –** Increases cetane number and improves lubricity.

The oils tend to be low in FFAs, making the transesterification reaction easier and resulting in greater biodiesel yield.

Components in Animal Fat-Based Biodiesel

Animal fats are full of saturated fatty acids, which provide higher oxidative stability and cetane numbers. Unfortunately, they also melt at higher temperatures, leading to gelling under low temperatures. Typical constituents are:

- Palmitic Acid (C16:0)
- Stearic Acid (C18:0)
- Myristic Acid (C14:0)

Due to their solid state at room temperature, animal fat feedstocks tend to need preheating or mixing with vegetable oil biodiesel to improve cold flow characteristics.

1.3.4 Number of Times WCO is Considered Waste Oil

Cooking oil chemically and physically decomposes with repeated use. Every heat cycle lowers the nutritional and oxidative value of the oil, and eventually, it becomes unfit for human consumption.

Standards of Classifying WCO as Waste:

- When cooking oil is heated for frying above three times, it is usually considered waste cooking oil (WCO).
- Numerous studies have shown that reused oils for deep frying contain peroxides, FFAs, and polar compounds above safe health levels.

1.4. BIODIESEL PRODUCTION PROCESS

The production of bio–diesel oil from waste cooking oil (WCO) is mainly done by a transesterification reaction, a chemical process that has been shown to convert neutral fat (the main ingredient of fat and oil). Methyl ester and glycerol. The reaction is basic for converting low raw materials at low prices like WCO into a useful and reconstructed fuel source. The inherent goal of the transesterification process is hydro triglycerides with lower molecules, then can be used as fuel in diesel engines.

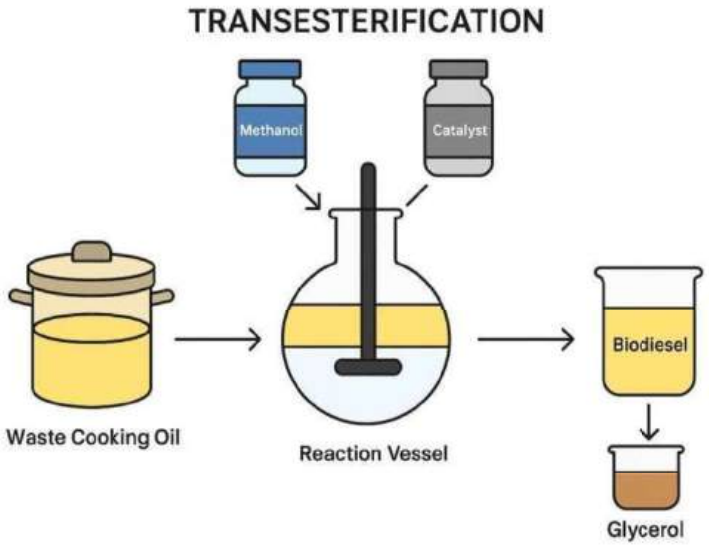


Figure: 1.2.- Biodiesel Production Process.

1.4.1 Transesterification Reaction:

Chemical Mechanism

During Transesterization, an alcohol molecule, usually methanol (CH_3OH) or ethanol (C_2H_5OH), exchange a group of esters from a neutral fat (the main fat molecule includes a glycerol molecule associated with three acids fat). Glycerol ($C_3H_8O_3$) and Este Methyl (biological diesel, CH_3COOR) are formed in this reaction, catalyzed by a basic or an acid and including triglyceride (C_3HH_5 (OCO-R)) and alcohol (R-Oh). The answer can be written as:

$$\boldsymbol{Triglyceride + 3Methanol \xrightarrow{Catalyst} 3Methyl\ Esters\ (Biodiesel) + Glycerol}$$

- Triglycerides are fatty molecules from WCO, animal fats, or vegetable oils.
- The alcohol involved in the esterification reaction is methanol, which is at times referred to as ethanol.
- The catalyst is required to accelerate the reaction and facilitate the conversion.

1. Phases of Reaction

There are three steps typically incorporated in the process of transesterification:

Stage 1: An intermediate diester and monoglyceride are formed when the initial alcohol molecule reacts with the triglyceride molecule.

Stage 2: A monoester and a diglyceride intermediate are produced as the second alcohol molecule reacts with the monoglyceride intermediate.

Stage 3: The diglyceride is reduced to glycerol and the end product, methyl esters (biodiesel), by the last reaction.

There needs to be a catalyst at each step of the reaction to split the ester bonds of the triglyceride and ensure complete reaction. The efficiency of such processes and the stoichiometric methanol to triglyceride ratio decide the overall amount of biodiesel that is produced

Steps in The Transesterification Process

Step 1: Oil Pre-Treatment (Removal of Impurities)

The transesterification reaction, it is critical to treat the oil feedstock whether from vegetable oils, animal fats, or waste cooking oil (WCO) with a rigorous pre-treatment process to maximize reaction efficiency and biodiesel yield. The pre-treatment process entails the elimination of several impurities that negatively impact the reaction, such as moisture (water content), suspended solids, food residues, and especially free fatty acids (FFAs). Water content can cause hydrolysis reactions, whereas solid impurities can lead to mechanical problems during processing. Above all, high FFAs content is not desired since they will react with the alkaline catalysts, e.g., sodium hydroxide or potassium hydroxide, to produce soap by the process of saponification and will affect the separation between glycerol and biodiesel and reduce biodiesel yield considerably. In response to this, feedstocks with high levels of FFAs, including WCO, are typically subjected to acid esterification in which FFAs are transformed into esters prior to the bulk transesterification reaction. Otherwise, physical pre-treatment by means of filtration, centrifugation, or settling is applied to purge off particulates and surplus water. Pre-treatment is an essential factor governing the ultimate success, efficacy, and economy of biodiesel manufacture.

Step 2: Reaction with Alcohol

Following the pre-treatment stage, the refined oil feedstock is treated in the core transesterification reaction by blending with an alcohol, typically methanol, but occasionally ethanol is employed with an appropriate catalyst which could be alkaline (NaOH or KOH) or acidic (H_2SO_4), based on the content of free fatty acid in the oil. The intention at this stage is to bring about a chemical reaction between triglyceride molecules in the oil and the alcohol, which leads to the breaking of ester bonds and the formation thereafter of fatty acid methyl esters (FAMEs), which form biodiesel, and glycerol as a by-product. Theoretical ratio for reaction is 3:1 triglycerides and alcohol but it is raised usually to around 6:1 or higher levels in practice so that complete conversion of triglycerides into biodiesel may occur and for efficient overall yield and performance. Extra alcohol will further cause shift towards product in Le Chatelier's principle of the reaction's equilibrium. This process is at the heart of biodiesel production and needs to be carefully managed in terms of temperature, duration, and catalyst concentration to produce a high-quality fuel product [15].

Step 3: Role of Catalyst in the Reaction

Catalysts are extremely important in transesterification as they have the effect of greatly speeding up the reaction between triglycerides and alcohol so that oil is efficiently converted into biodiesel and glycerol. Even though the catalyst is not consumed throughout the reaction, it aids the cleavage of ester links in triglyceride molecules that would otherwise mean longer reaction periods and increased energy input. Selection of catalyst is critical and is mostly dependent on the free fatty acid (FFA) concentration of the feedstock. For low FFA-containing oils, the alkaline (base) catalysts like sodium hydroxide (NaOH) and potassium hydroxide (KOH) are more desirable because of their high activity, affordability, and the ability to achieve complete reaction at relatively low temperature and brief reaction time. But if the oil has high FFAs as in the case of waste cooking oil (WCO), alkaline catalysts can lead to saponification and soap formation, which inhibits the separation of glycerol and biodiesel. Acid catalysts such as sulfuric acid (H_2SO_4) or hydrochloric acid (HCl) are better suited in such situations since they esterify FFAs and inhibit soap formation, although they need longer reaction times and higher operating temperatures. Therefore, the choice and concentration of the catalyst directly influence the efficiency of the reaction, the purity of the biodiesel, and the economic feasibility of the production process.

Catalysts are important in transesterification, which is a chemical reaction extensively utilized for biodiesel manufacturing. Their primary function is to lower the activation energy required for the reaction, which will boost its rate and enable it to proceed effectively in more modest circumstances. The yield, reaction time, and overall process viability are all significantly impacted by the catalyst. The three primary types of catalysts utilized in transesterification are enzymes, base catalysts, and acid catalysts. The amount of free fatty acid (FFA) in the used oil largely determines the strength of these, which are tailored to specific feedstocks.

a) Base Catalysis (Alkaline Catalysts)

The most popular method for producing biodiesel is base-catalyzed transesterification due to its great efficiency and relative affordability. For this, a catalyst, such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), is utilized. An alkoxide ion is produced when the alcohol, typically methanol, reacts with the base catalyst. This alkoxide, which is a nucleophile, then attacks the carbonyl carbon of triglyceride molecules. Triglycerides are hydrolyzed in this process, yielding glycerol as a by-product and methyl esters (biodiesel).

The general chemical reaction for transesterification catalyzed by a base is:

$$\boldsymbol{Triglyceride + 3Methanol + Base\ Catalyst(NaOH\ or\ KOH)}$$
$$\boldsymbol{\rightarrow 3Methyl\ Esters\ (Biodiesel) + Glycerol}$$

One of the biggest benefits of base catalysis is its high rate of reaction, enabling biodiesel to be manufactured comparatively fast as opposed to other processes. Base catalysts are the ideal choice for producing biodiesel on a wide scale since they are readily available and reasonably priced. However, the amount of free fatty acid (FFA) in the feedstock has a significant impact on the process. The saponification reaction between FFAs and the base catalyst causes soap to develop if the oil contains a high concentration of FFAs. Soap formation not only lowers the yield of biodiesel but also makes glycerol separation from the product difficult. In addition, the feedstock should be free from water and other contaminants to avoid side reactions that can lower the efficiency and degrade the catalyst.

b) Acid Catalysis

Compared to base catalysis, acid-catalyzed transesterification is less susceptible to feedstock free fatty acids. A catalyst like hydrochloric acid (HCl) or sulfuric acid (H2SO4) is used in this process. Acid catalysis uses a different reaction mechanism in which the acid catalyst protonates the carbonyl oxygen atom of the triglyceride molecule, making it more electrophilic. This allows the nucleophilic attack of methanol and thus produces methyl esters (biodiesel) and glycerol.

The acid-catalyzed transesterification reaction is as below:

$$\boldsymbol{Triglyceride + 3Methanol + Acid\ Catalyst(H2SO4)}$$
$$\boldsymbol{\rightarrow 3Methyl\ Esters\ (Biodiesel) + Glycerol}$$

The ability of acid catalysis to process low-quality feedstocks, such as leftover cooking oil and animal fats, which often include a high FFA level, is one of its key advantages. Acid catalysts are more adaptable when it comes to feedstock selection because they don't produce soap. However, there are certain disadvantages to the procedure. Compared to base-catalyzed transesterification, acid-catalyzed transesterification proceeds significantly more slowly and usually necessitates prolonged reaction durations and high temperatures in order to produce satisfactory yields. Moreover, employment of strong acids calls for special handling because of their extreme corrosiveness, and acid residue disposal contributes to the cost of the process.

c) Enzyme Catalysis (Lipase Enzyme Catalysts)

Enzyme-catalyzed transesterification is now a novel method that provides specific advantages compared to chemical catalysts. Lipase enzymes from microorganisms catalyze triglyceride esterification with alcohols under comparatively mild conditions of reaction. Enzyme catalysis involves no severe chemicals and works efficiently at moderate pressures and temperatures, thus proving to be environmentally benign.

Triglyceride molecules selectively attach to the lipase enzyme's active site as part of the reaction mechanism in enzyme-catalyzed transesterification. The enzyme catalyzes the conversion of alcohols and triglycerides into glycerol and methyl esters. Due to the high substrate specificity of lipases, they are able to catalyze reactions efficiently even with free fatty acids without inducing soap formation.

The enzyme-catalyzed transesterification reaction equation is very similar to that of acid and base catalysis:

$$\boldsymbol{Triglyceride + 3Methanol + Lipase\ Enzyme}$$
$$\boldsymbol{\rightarrow 3Methyl\ Esters\ (Biodiesel) + Glycerol}$$

One of the advantages of enzyme catalysis is that it is carried out under mild conditions, minimizing the possibility of unsolicited side reactions. Lipase enzymes are also reusable several times, and so the process can be made economical and sustainable for some applications. The limitation nevertheless remains the significant cost of the production and purification of enzymes. In addition, the activity of enzymes can be deactivated by contaminants like water and excess alcohol, thereby influencing the overall efficiency of the process.

The catalyst choice in transesterification is important to maximize biodiesel production. Base catalysts are used because of their quick reaction rate and low cost but demand feedstocks that are highly purified and have low FFA levels. Acid catalysts, though slower and costlier, are more flexible in their ability to process high-FFA feedstocks without soap formation. Enzyme catalysts represent a green technology with high selectivity and reusability, but with limitations of high price and susceptibility to contamination for their extensive application. There are advantages and disadvantages of each type of catalyst, and the choice of suitable catalyst will depend on the composition of the feedstock, economic viability, and requirements of process efficiency.

Step 4: Separation and Purification of Biodiesel and Glycerol

The transesterification reaction, the reaction mixture is two immiscible liquid layers because the products have differing densities and polarity: the dense glycerol layer, with excess unreacted catalyst, remaining alcohol, and soap, is at the bottom, whereas the lighter biodiesel layer (fatty acid methyl esters) is at the top. The initial step in post-reaction processing is the separation of these two layers, and this can be done through simple gravity settling so that the denser glycerol sinks naturally or through centrifugation so that the process is accelerated using centrifugal force. The separated crude biodiesel still has impurities like residues of methanol, soap, catalyst residues, and suspended solids, which have to be removed to meet the fuel quality requirements. This is done by a washing process, most commonly multiple warm water rinses to remove the soluble impurities. After the washing step, the biodiesel needs to be dried out completely to remove all remaining water content, since excess moisture will lead to poor combustion efficiency and microbial contamination during storage. The resulting pure biodiesel is transparent, passes ASTM or EN standards for biodiesel fuel, and can be used directly in diesel engines as pure or mixed with petroleum diesel. The correct separation and purification are key to providing the final biodiesel product's high performance, stability, and safety [16].

Step 5: Glycerol Recovery

The transesterification reaction is complete and the biodiesel layer has been separated from the glycerol, this useful by-product is not waste but a commercially valuable substance which can be recovered, purified, and reused for a variety of industrial purposes. Raw glycerol, when recovered directly from the biodiesel process, often has impurities like unreacted methanol, soap, catalyst residues, and water and needs to be purified by treatment processes like distillation, neutralization, and filtration. Once purified, glycerol turns into a generic compound with appreciable demand from many industries. In the medicine industry, glycerol acts as a solvent, humectant, and additive in cough medicines and syrups. In the cosmetic and personal care industry, glycerol acts as a prime moisturizer in creams, lotions, and toothpaste. Glycerol is used in the food sector as a sweetener, a preservative, and a texturizer for baked foods and processed foods. It is used extensively in soap manufacturing and finds new applications in bioplastics, antifreeze, and as a raw material for biogas production and hydrogen generation. The valorization of glycerol not only contributes to the economic value of the biodiesel production process but also makes it environmentally sustainable by fostering a zero-waste,

circular economy model in which both primary and secondary products of the process are utilized optimally [17].

1.4.2 Factors Affecting Transesterification Efficiency

A number of factors impact the yield and efficiency of transesterification. The optimization of these factors is necessary to ensure high biodiesel yields with cost-effectiveness and process viability.

1. Molar Ratio of Alcohol to Triglyceride

One of the most crucial transesterification characteristics is the molar ratio of alcohol to triglycerides. Raising the molar ratio promotes high efficiency in the conversion of triglycerides to biodiesel and ensures a complete reaction. In base-catalyzed transesterification, the typical molar ratio used is between 6:1 and 12:1. A mole of triglyceride will react with three moles of alcohol at a stoichiometric ratio of 3:1 needed for transesterification; but, for practical reasons, there is more alcohol than that since an excess propels the reaction forward to provide full conversion and a good yield.

Nonetheless, the high use of alcohol results in a high cost of separation since excess alcohol must be recovered and recirculated. Additionally, too much alcohol in enzyme-catalyzed transesterification inhibits enzyme activity, decreasing the efficiency of the reaction.

$$\boldsymbol{Triglyceride + 3Methanol \rightarrow 3Methyl\ Esters\ (Biodiesel) + Glycerol}$$

For acid-catalyzed transesterification, there may be a necessity for a higher molar ratio (for instance, 10:1 or 12:1) due to retarded kinetics.

2. Temperature and Reaction Time

Transesterification is a temperature-sensitive process, and a judicious operating temperature improves the reaction efficiency.

- A usual temperature between 60-65°C for base-catalyzed transesterification has been suggested. This temperature range is nearly identical to methanol's boiling point (64.7°C) and permits thorough mixing and reaction without causing significant methanol evaporation.
- Acid-catalyzed reactions need higher temperatures (80-100°C) because the reaction kinetics is slower.

- Transesterification occurs by enzyme catalysis at 30 -50°C because high temperatures may denature enzymes.

The response time is catalyst and reaction conditions dependent:

- Base-catalyzed transesterification typically requires 1-5 hours for complete conversion.
- Acid-catalyzed reactions take longer and require 4-8 hours or more.
- Enzyme-catalyzed reactions can take 6-24 hours depending on enzyme activity and substrate concentration.

Longer reaction time tends to enhance conversion but can become too long to cause undesirable side reactions, e.g., soap formation in base-catalyzed reactions.

3. Stirring and Mixing

Proper mixing is required to achieve good contact among triglycerides, alcohol, and the catalyst. Because oil and alcohol are immiscible, poor stirring may cause phase separation, thus lowering reaction efficiency.

- High-speed mechanical agitation enhances mass transfer and increases the rate of reaction.
- Ultrasonic mixing can improve transesterification by inducing cavitation, enhancing the reaction surface area.
- Excessive shear forces can inactivate enzymes in enzyme-catalyzed systems, hence gentle stirring is advisable.

Effective stirring reduces the reaction completion time and boosts biodiesel yield.

1.5 ADVANTAGES OF USING WCO FOR BIODIESEL PRODUCTION

The use of waste cooking oil (WCO) as a fuel stock for biological diesel production has increased great interest in the past decade due to countless environmental, economic and social advantages. WCO, often wasted after use in cooking, can be converted into a valuable product by undergoing transesterification to produce biological diesel oil. This method not only addresses waste treatment issues, but also supports sustainable energy production and circulating economy. Some of the main advantages of using WCO in the production of biological diesel are listed below:

Waste Reduction and Environmental Benefits

One of the main benefits of utilizing WCO for the production of biodiesel is minimizing waste. WCO, when disposed of improperly, can become major environmental pollutants. When discharged into drains or into the environment, it may result in soil contamination, water pollution, and negative impacts on aquatic organisms. Utilizing this waste oil to produce biodiesel means that we are minimizing the environmental impact that it would otherwise create if it were disposed of improperly.

- **Collecting Waste Cooking Oil:** Rather than be dumped into landfills or sewers, WCO can be collected, strained, and processed to produce biodiesel. Such recycling of waste is in consonance with the tenets of the circular economy, where materials and products are made to last as long as possible, so that waste generation is minimized and the environmental cost of waste products is reduced.
- **Decrease in Landfill Waste:** Through the use of WCO to produce biodiesel, waste sent to landfills is lessened considerably. This, further, reduces pressure on waste management systems and also lessens landfill sites' effects on the environment, which, in most cases, are usually linked to leachate contamination and methane gas emissions [18].

Economic Advantages

Application of WCO for the manufacture of biodiesel has a number of economic advantages, ranging from cost reduction to generation of income.

- **Low-Cost Feedstock:** WCO is generally a much cheaper feedstock than virgin vegetable oils or any other feedstock used to make biodiesel. WCO is usually a waste material, so it can be sourced for very cheap or even absolutely free from restaurants, food processing companies, and other food-related establishments. This renders production of biodiesel from WCO economically viable, particularly compared to biodiesel that is produced using high-priced virgin oils like palm oil or soybeans.
- **Lesser Fossil Fuel Dependence:** Through the production of biodiesel from WCO, nations and companies can lower their dependence on foreign fossil fuels whose prices can fluctuate unpredictably in the world market and on which there could be geopolitical conflicts. WCO-derived biodiesel can stabilize the price of energy and

improve the energy security of nations that have restricted access to traditional petroleum resources.

- **Economic Opportunities:** The gathering, processing, and conversion of WCO to biodiesel can generate new economic opportunities across different sectors. Enterprises that are engaged in the collection and transportation of used cooking oil and those that have biodiesel production plants can create local employment opportunities. Moreover, new technologies associated with the biodiesel sector, including improved purification systems and advanced catalytic systems, can lead to further development and employment generation in the green energy sector.

Sustainability and Renewable Energy Production

Biodiesel produced by WCO is a renewable and long-lasting energy source. Because it is a biofuel, diesel engines can use it to replace non-renewable fossil fuels and reduce carbon emissions overall [19].

- **Carbon Footprint Reduction:** The combustion of biodiesel puts out (CO_2) in the environment; nevertheless, the emitted CO_2 is a part of natural carbon recycling. The crops from which WCO is derived absorbed CO_2 when they grew up, and by reusing the oil into biodiesel, the net emission of CO_2 is much less than using regular diesel. This renders WCO-based biodiesel a carbon-neutral fuel, aiding in climate change mitigation through the reduction of the overall greenhouse gas emissions of the energy and transportation sectors.
- **Sustainable Energy Transition:** Utilization of WCO as a feedstock aids the world in transitioning towards more sustainable energy systems. In contrast to fossil fuels, which are limited and cause environmental degradation, biodiesel from WCO is renewable and can be manufactured indefinitely provided there is waste oil. This contributes to a more sustainable and resilient energy environment, less dependent on conventional fossil fuels and leading to a cleaner future.

Contribution to Biodiversity and Land Use

One of the benefits of applying WCO to the production of biodiesel is its lesser land use and biodiversity impact.

- **No Need for Additional Land:** In contrast to other biofuels, which are made from agricultural produce such as corn, soybeans, or palm oil, WCO biodiesel production

does not necessitate additional land for agriculture. This circumvents the conflict with valuable land that causes deforestation, habitat destruction, and biodiversity loss for large-scale biofuel development.

- **Natural Resource Conservation:** By depending on WCO, we conserve valuable natural resources, such as land, water, and labour, that would otherwise be needed to cultivate and harvest crops for use in biofuel manufacturing. This renders biodiesel based on WCO a greener option compared to biofuels produced from food crops, which can have unforeseen environmental consequences.

Improvement of Energy Access and Rural Development

Bio Diesel WCO can improve access to energy and rural development, especially when there is a rare approach to providing normal energy [20].

- **Local energy production:** WCO Bio Diesel can be produced in the locality, making communities more independent of energy. This may be especially important in rural communities, where energy access may be trivial or inconsistent. By creating biological diesel from local WCO, communities can improve their energy security and minimize their dependence on expensive imported fuel.
- **Supports rural economy:** Revenue collected in local restaurants, food sellers and companies through WCO can create additional income sources for small collectors and Rural businessman. This stimulates rural economies, improves livelihoods and encourages sustainable business activities in areas that may suffer economic difficulties.

Positive Impact on Health

The use of WCO to produce biological diesel oil can also be good for health, especially when considering the burning of traditional diesel fuel.

- **Lower Air Pollution:** WCO Bio Diesel releases much lower air pollutants such as sulfur dioxide (SO_2), particles and hydrocarbons are not motivated compared to oil diesel. This can lead to a better decline in air pollution and public health, especially in urban centers with high emissions. Weaker emissions can lead to cleaner air, few cases of respiratory diseases and better overall environmental quality.

The use of waste oil (WCO) as raw materials to produce biological diesel has many advantages, from environmental protection, economic benefits and sustainable support. By maintaining resources, preventing pollution and developing renewable energy, WCO Bio Diesel helps to

switch to a long -term energy future. In addition, it provides economic prospects and improves rural development while slowing the dependence on fossil fuels and energy security progress. In many aspects, the application of WCO in biological diesel production is a long -term and long -term method to solve some of the most urgent problems in our era.

- **Greenhouse Gas Emission Reduction**

One of the most significant environmental benefits of biodiesel is its huge potential to lower greenhouse gas (GHG) emissions relative to traditional petroleum-based diesel. As global warming worsens and global regulations call for lower carbon emissions in energy systems, biodiesel provides a cleaner burning profile, positively impacting air quality and global emissions goals. Biodiesel lowers GHG emissions by a large margin relative to petroleum diesel. These include significant pollutants like:

- **Carbon Dioxide (CO_2)**

The burning of fossil fuels such as petroleum diesel unlocks carbon stored under the ground for millions of years, contributing to atmospheric CO_2 levels and widening global warming. On the contrary, biodiesel is made from modern biological origin sources such as vegetable oils, animal fats, and waste cooking oils. They come from crops that uptake CO_2 when photosynthesizing. Consequently, the carbon dioxide emitted when biodiesel is burned is approximately equal to the quantity already taken in by the plants that were utilized to make the fuel creating a closed carbon cycle. Although certain emissions are produced when biodiesel is manufactured and transported, lifecycle analyses always reveal a net CO_2 emission reduction of as much as 78% compared to petroleum diesel.

- **Sulfur Dioxide (SO_2)**

Petroleum diesel has high levels of sulfur, which, during combustion, produces sulfur dioxide (SO_2) a primary cause of acid rain and respiratory diseases. Biodiesel, on the other hand, has little to no sulfur content, varying with the feedstock and production quality. This intrinsic property renders biodiesel much more environmentally friendly, particularly in areas with high vehicle population and strict sulfur emission regulations. The removal of SO_2 emissions from fuel sources also diminishes the corrosive effect on engine parts and infrastructure.

- **Carbon Monoxide (CO)**

Carbon monoxide is a harmful gas produced through incomplete combustion of carbon-based fuels. Petroleum diesel, particularly from older engines or in less-than-ideal combustion

conditions, yields high CO emissions. Biodiesel, as a result of having more oxygen content, Favors complete combustion, thus producing reduced carbon monoxide emissions. This makes biodiesel especially useful in urban areas, where high traffic densities lead to increased CO levels and serious health concerns for occupants.

- **Unburned Hydrocarbons and Particulate Matter (PM)**

Another significant diesel combustion pollutant is particulate matter (PM) microscopic solids and liquid droplets that can penetrate deep into the lungs and bloodstream. These particles, usually created as a result of unburned hydrocarbons, are associated with serious respiratory diseases, cardiovascular illness, and premature death. Biodiesel has been found to lower PM emissions significantly, partly because of its oxygen-rich composition and absence of aromatic hydrocarbons. Various studies have reported PM emission declines of 30% to 50% using biodiesel, depending on the engine type and blend. This leads to cleaner emissions and helps improve public health.

- **Nitrogen Oxides (NO_x)**

Nitrogen oxides, such as NO and NO_2, are major contributors to ground-level ozone and smog formation, causing respiratory problems and environmental damage. Although emissions are lowered by most of the biodiesel, research has found a minimal increase in NO_x emissions for some biodiesel blends, especially in aged engines. The increase is mostly due to increased combustion temperatures caused by improved oxygenation. Yet, progress is being made in engine calibration, exhaust after-treatment technologies, and the utilization of fuel additives to counteract this problem. New biodiesel-compatible engines now exhibit controlled NO_x levels equal to or below those of petroleum diesel.

Biodiesel considerably surpasses petroleum diesel in its environmental emissions. It reduces levels of CO_2, CO, SO_2, PM, and hydrocarbons considerably, adding to cleaner air and fewer health risks. Though the issue of slightly higher NO_x still remains, consistent technological advancements are constantly narrowing the gap. All these emission advantages make biodiesel an important part of sustainable fuel plans and city air quality management plans.

- **Biodegradability and non-toxicity**

One of the most visible environmental advantages of biodiesel over petroleum diesel is its higher biodegradability and lower toxicity level. These characteristics render biodiesel a more environmentally friendly and safer fuel, particularly in situations where environmental

pollution is a high-risk factor such as marine environments, agricultural fields, and aquatic areas. The biodegradability and non-toxicity of biodiesel minimize the environmental impact of accidental spills, fuel leaks, and improper disposal, thus contributing to ecological conservation.

- **Rapid Biodegradation**

Biodiesel has a high biodegradation rate based on its chemical makeup, which is mainly constituted by fatty acid methyl esters (FAMEs). FAMEs are naturally occurring substances that are extracted from plant oils and animal fats. They are thus more prone to microbial degradation. Petroleum diesel, on the other hand, consists of complex aromatic hydrocarbons and long-chain alkanes, which are significantly more resistant to biodegradation.

Research has proven that in conditions conducive to environment (i.e., suitable temperature, microbial process, and amount of oxygen), biodiesel would be degraded three times or four times faster compared to petroleum diesel. For example, whereas diesel lasts for several months or even years in both soils and bodies of water, biodiesel is known to degrade biologically after just 28 days, far reducing the exposure and severity of the environmental damage when spilled. This immediate decomposition also reduces the risk of long-term ecological damage and aids in speeding up natural recovery mechanisms.

- **Low Ecotoxicity**

Biodiesel exhibits minimal toxicity to aquatic and terrestrial life, and is consequently much safer for the environment. Released into aquatic systems, petroleum diesel induces acute and chronic fish, amphibian, invertebrate, and plant toxicity by means of toxic hydrocarbons and additives. Biodiesel, on the other hand, has no substantial levels of toxic substances like sulfur, benzene, or polycyclic aromatic hydrocarbons (PAHs), and does not bioaccumulate in the food web.

Toxicity tests have shown that biodiesel is not toxic to aquatic life even at comparatively high concentrations. Since it degrades into harmless components like carbon dioxide, water, and biomass, it is perfectly suitable for sea transport, agricultural equipment, and construction equipment used in the vicinity of ecologically sensitive regions. In addition, the lower production of surface films or emulsions by biodiesel reduces physical asphyxiation of aquatic flora and fauna commonly seen in petroleum spills [24].

- **Reduced Carcinogenic and Mutagenic Risks**

Petroleum diesel includes numerous toxic and carcinogenic chemicals, including polycyclic aromatic hydrocarbons (PAHs) and nitroaromatic compounds, that have been found to cause groundwater contamination, soil toxicity, and harmful effects on human health, including cancer, reproductive damage, and genetic mutation. These chemicals are not only persistent but also bio accumulative, and their long-term exposure causes harm to human and environmental health.

Conversely, biodiesel is derived from natural feedstocks and is PAH-free and synthetic additive-free. It does not contain volatile organic compounds (VOCs) and other pollutants that are ubiquitous in diesel smoke and residues. As a result, biodiesel drastically minimizes the risk of human and wildlife populations' exposure to carcinogens. Its use in environmentally sensitive regions therefore adds to cleaner water quality, fertile soil, and biodiversity conservation.

❖ **Lower Carbon Footprint and Sustainability**

Biodiesel enables a circular carbon economy:

- It is drawn from plants which capture atmospheric CO_2, whose lifecycle emissions are significantly lower compared to fossil fuels.
- Employment of second-generation feedstocks, waste oils, and non-food crops enhances sustainability by eliminating competition with food supply.
- Recycling waste cooking oil (WCO) lessens land and water contamination and provides an additional source of revenue from kitchen wastes.

❖ **Other Environmental Advantages**

Aside from the widely acknowledged benefits of lowered emissions and improved biodegradability, biodiesel has some other important environmental and socio-economic benefits. The benefits make biodiesel an interesting part of sustainable energy policies all over the world. Some key benefits include the ability to substitute fossil fuels, compatibility with existing infrastructure, and rural development and economic growth contributions.

- **Fossil Fuel Replacement**

One of the strategic environmental functions of biodiesel is that it can act as a replacement for finite fossil fuel resources. Crude oil, natural gas, and coal are finite, non-renewable resources

that make a significant contribution to environmental degradation in their extraction, refining, and burning processes. By substituting part of diesel fuel consumption with biodiesel—particularly blends such as B20 (20% biodiesel, 80% diesel) and B100 (straight biodiesel)—nations can dramatically decrease their dependence on petroleum imports and fossil fuel production activities.

Production of biodiesel comes from renewable biological feedstocks such as vegetable oils, animal fats, and waste oils that are renewable on a relatively short-term basis in relation to the geological timescales of fossil fuel production. In so doing, not only does biodiesel increase energy security, but it also lessens the geopolitical threats inherent with oil supply variations and volatility of global petroleum markets. In addition, the transition to biofuels reduces the environmental impacts associated with oil drilling, refining, and transportation, including oil spills, land degradation, and loss of habitat.

- **Infrastructure Compatibility**

One of the most important practical benefits of biodiesel is its excellent compatibility with current diesel infrastructure. Biodiesel can be used in conventional diesel engines without the need for considerable modifications, particularly in blends. Even at higher blends such as B100, only slight adjustments may be needed, mainly related to the fuel hoses and gaskets made from materials incompatible with biodiesel's solvent characteristics.

In the same way, biodiesel may be stored, processed, and shipped within existing petroleum diesel pipelines, storage facilities, and refuelling stations, permitting an easy transition to cleaner fuels with no major investment in new distribution infrastructure. This compatibility makes the introduction of biodiesel much easier and hastens its incorporation into existing transportation and industrial systems. It also results in reduced overall lifecycle emissions as no new infrastructure development (and attendant environmental burdens) is required.

In addition, the increased lubricity of biodiesel over petroleum diesel enhances the efficiency and durability of engines as wear and tear on engine parts is minimized, translating to minimal maintenance costs and increased vehicle lifespans.

- **Rural Development**

Production of biodiesel presents huge possibilities for rural economic growth and poverty reduction. Because the major raw materials for producing biodiesel, including soybean oil, canola oil, jatropha oil, and animal fats, come from agriculture and livestock production, the

development of the biodiesel industry indirectly benefits farmers, rural cooperatives, and small-scale producers.

The biodiesel sector generates markets for energy crops, leading to diversified agricultural operations that boost farm revenues and make farmers less dependent on conventional commodity crops that could be exposed to market instability. It also ensures value addition in rural areas because farmers and rural entrepreneurs are involved in activities beyond cultivation, like oil extraction, feedstock processing, and micro-scale biodiesel production.

Besides, employment in industries such as seed production, cultivation of crops, oil processing, fuel refining, distribution, and maintenance services enhances the socio-economic fabric of rural areas. Biodiesel projects supporting sustainable agricultural practices also enhance soil conservation, water management, and ecosystem integrity, reinforcing environmental resilience of rural landscapes.

Therefore, biodiesel production is a two-way advantage: it promotes cleaner energy systems and renews rural economies, furthering sustainable development goals (SDGs) concerning clean energy, decent work, economic growth, and sustainable production.

1.6. GLOBAL TRENDS IN WASTE COOKING OIL UTILIZATION

The use of Waste Cooking Oil (WCO) to create biodiesel is an integral component of a worldwide pattern aimed at sustainability, the reduction of wastage, and alleviating environmental damage from the conventional fossil fuel. With the increase in environmental challenges, nations, and sectors turning towards sustainable measures for countering energy deficits, pollution concerns, and deficiencies of resources, WCO converting to biodiesel is a leading sector in circular economics. Different nations have started adopting policies and technologies that utilize this previously underutilized resource to realize economic growth, energy self-sufficiency, and environmental protection. This chapter discusses the increasingly popular global movement of WCO utilization and application in the waste management and energy industries.

1.6.1 Global Adoption of Waste Cooking Oil in Biodiesel Production

1. Rising Demand for Sustainable Biofuels

One of the primary factors that is driving the use of Waste Cooking Oil (WCO) in the production of biodiesel is the rising international demand for energy sources that are both renewable and sustainable. Governments, businesses, and research organizations are looking

for alternative energy options that minimize environmental footprints while maintaining energy security as concerns about climate change, fossil fuel exhaustion, and greenhouse gas emissions grow.

Biodiesel, a sustainable energy source made from various feedstocks like vegetable oils, animal fats, and waste oils, is recognized as a key component in the global transition to greener energy. In particular, WCO is growing in popularity due to its benefits in terms of accessibility, cost, and sustainability. WCO has been integrated as a primary feedstock in the biodiesel value chains of states with clear biofuel mandates, including the US, Brazil, and numerous European nations. Commercial-scale plants now use WCO in conjunction with other materials such as soybean oil, palm oil, and animal fat, lowering the reliance on virgin feedstocks and lessening deforestation issues associated with crops such as palm oil.

In addition, the transport industry one of the biggest emitters of carbon globally is increasingly using biodiesel blends as a clean substitute for regular diesel. Government policies in several regions require blending biodiesel with regular diesel, driving the demand for WCO-based biodiesel and the development of collection and processing networks for waste oils.

2. Economic Incentives and Policy Support

Governments everywhere are establishing fiscal incentives and regulatory policies that promote the use of alternative, non-food-based feedstocks in a bid to accelerate the adoption of WCO as a biofuel feedstock. Producers and consumers alike are incentivized to shift to biodiesel by policy measures such as tax credits, incentives, subsidies, and blending mandates. The European Union's Renewable Energy Directive (RED II), for instance, is on a fast track to meet ambitious targets for renewable energy and mandates the use of a percentage of transportation fuels from sustainable origins, including advanced biofuels such as WCO's biodiesel. The rule also spurs the transition to waste-based biofuels by discouraging the use of land-use change and deforestation-associated feedstocks.

In India, the government has launched the National Bio-Energy Mission and programs such as the Repurpose Used Cooking Oil (RUCO) initiative, which promotes the collection of WCO from households and food service providers to process it into biodiesel. India's biofuel policies seek to lower the reliance on imported crude oil, increase energy security, and foster a circular economy by repurposing waste. China has also enacted laws to suppress illegal recycling of waste cooking oil for food purposes and redirect it for use in the production of biodiesel. The

Chinese government has subsidized the collection of WCO, and the industry has grown rapidly as a result [25].

In the US, the makers of biodiesel enjoy the Renewable Fuel Standard (RFS) program that requires mixing renewable fuels with the country's fuel supply. Tax credits like the Biodiesel Tax Credit (BTC) also increase the economic feasibility of WCO-based biodiesel manufacture. The policy helps not only towards sustainability objectives but also towards opportunities for business in waste oil gathering and biodiesel manufacturing industries.

3. Technological Advances in Biodiesel Production

The smooth integration of WCO into biodiesel processing has been facilitated through impressive breakthroughs in processing technologies. WCO was initially considered less favourable due to high free fatty acid (FFA) levels, impurities, and oxidation compared to virgin oils. Contemporary innovations, however, enhanced both the cost-effectiveness and efficiency of WCO conversion into high-quality biodiesel.

New transesterification technologies, where WCO is reacted with alcohol and a catalyst, have been designed to accommodate high-FFA feedstocks, reducing the necessity for further refining. The development of heterogeneous catalysts and enzyme catalysts (e.g., lipase enzymes) has improved biodiesel yields while minimizing waste by-products. These emerging catalysts enhance reaction rates and enable more sustainable processing through the reduction of excessive chemical inputs.

Moreover, improved filtration, degumming, and purification processes now enable efficient removal of impurities like food particles, water content, and polymerized fats from WCO prior to biodiesel conversion. As these technologies improve, the production cost of biodiesel from WCO will go down, and it will become an even more viable substitute for petroleum diesel.

4. Waste-to-Energy Integration

Apart from biodiesel manufacturing, WCO is being increasingly utilized in more comprehensive waste-to-energy ventures. Numerous urban municipal waste management corporations and municipal authorities are setting up systematic collection schemes for post-consumer and food processing unit waste cooking oils from households, restaurants, and food processing units. These are subsequently processed and reused in numerous energy applications, leading towards a circular economy.

For example, WCO is utilized in the production of biogas where it is processed through anaerobic digestion to produce methane-enriched biogas that can be employed for electricity or as a direct replacement for natural gas. A few waste-to-energy facilities co-process WCO with other organic waste streams in order to produce higher yields of biogas.

Besides that, WCO can also be utilized in hydrotreated vegetable oil (HVO) manufacturing, the next-generation biofuel with increased fuel quality that can be employed in aviation and maritime sectors. Utilizing WCO in manufacturing HVO gives another option to extract the best value from waste oils while cutting down on dependence on fossil fuels in industries which are notoriously difficult to decarbonize.

The growth of waste-to-energy programs has important economic and environmental advantages, such as:

- Landfill waste reduction by recycling used cooking oil
- Decreasing carbon emissions by substituting fossil fuels
- Opening up new business ventures in the waste management and bioenergy industries
- Improving local energy security through domestic production of sustainable fuels

As energy demands around the world keep on rising, and worries about climate change mount, WCO's role in the generation of renewable energy will become more critical. Investment in collection, processing, and conversion infrastructure will be necessary to upscale the inclusion of WCO in the energy industry.

1.6.2 Regional Trends and Initiatives

2. North America

In terms of producing biodiesel from waste oils like WCO, the US and Canada have taken the lead. The Renewable Fuel Standard (RFS) mandates that a growing proportion of renewable fuels, including biodiesel, be used in the transportation fuel pool, and the Biodiesel Tax Incentive encourages the production of biodiesel in the US. The American biodiesel industry, specifically, has experienced increased usage of WCO because of its lower price compared to virgin oils. In Canada, provinces and Alberta have launched programs to enhance the use of biological diesel and cities become more popular in the WCO collection to handle biological diesel factories. WCO is also used as raw materials in wastewater treatment, where it is used to produce biogas for energy.

3. Europe

EU renewable energy indicator has established highly renewable energy goals in the field of transport, which has increased the demand for biological diesel oil. Germany, France and the Netherlands have built large -scale facilities to convert WCO to biological diesel. EU waste frame indicator encourages recycling and reuse of waste, such as used oils, supports waste reduction and sustainable promotion.

4. UAE

In order to promote the manufacture of bio-diesel oil, including the use of WCO as a raw material, Dubai has put the national biofuel policy into effect. In an effort to reduce air pollution and meet its targets for renewable energy, In a new initiative that directly impacts households and restaurants across the emirate, Dubai has launched a major environmental project to collect and convert used cooking oil into biodiesel.

A partnership between Dubai Municipality and BiOD Technology FZCO, a subsidiary of DUBAL Holding. The move not only prevents clogged pipes and environmental harm but also contributes to Dubai's vision for a circular economy. Under a newly signed Memorandum of Understanding (MoU), BiOD Technology is authorised to collect used cooking oil (UCO) and fats, oils, and grease (FOG) from across the emirate and convert them into B100 biodiesel, a clean fuel alternative that helps reduce carbon emissions.

Figure:1.3.- A partnership between Dubai Municipality and BiOD Technology FZCO.



5. India

Kerala to convert used cooking oil into biodiesel. The New Indian Express) Around 60 tonnes of used cooking oil will be repurposed to biodiesel as part of the initiative. To ensure food safety and prevent health hazards owing to the consumption of used cooking oil, food business operators (FBOs) in the state comprising caterers, restaurants, hotels and bakers

have decided to be part of the Repurpose Used Cooking Oil (RUCO) - an initiative of Food Safety and Standards Authority of India (FSSAI). The plan is to hand over used cooking oil to an FSSAI accredited service provider to convert the same into bio -diesel.

6. China and Malaysia

Since 2013, the city has been experimenting with using biodiesel in public buses and street - cleaning vehicles. By the end of 2020, B5 biodiesel was available in all of the city's 243 filling stations. The name Eco Ceres comes from 'Ecology' and 'Ceres', the Roman goddess of agriculture. Initially founded as part of the Hong Kong and China Gas Company (Towngas), was turn to biomass waste into biofuels and bioproducts Using proprietary technology, we convert the used cooking oil into sustainable aviation fuel (SAF) and hydro-treated vegetable oil (HVO), which can be used as substitutes for aviation fuel and diesel, respectively, and we extract sugar from agricultural waste to produce cellulosic ethanol, which can be used as a blended substitute for gasoline. This specializes in providing decarbonization solutions for every major fossil fuel in the transportation sector.

1.6.3 Challenges and Opportunities

- **Challenges**

Although the trends of using WCO in the world are encouraging, there are still some challenges. The exploitation and cleaning of the WCO from different sources is expensive and poses logistics issues, especially in places where there is no infrastructure to collect waste oil infrastructure. Because WCO may contain pollutants that have an impact on the quality of biological diesel oil, there are also issues with quality control. The public's awareness of the negative environmental effects of the WCO's incorrect removal and the importance of recycling is another significant obstacle.

- **Opportunities**

Despite these disadvantages, WCO offers great opportunity to expand. Although more and more countries apply sustainable goals and increase their investments in renewable energy sources, the use of biofuel, including biological diesel oil produced from WCO, will see another peak. In addition, the process of biotechnology for biological diesel and partnership between companies managing waste and biological diesel manufacturers brings great potential to improve efficiency and volume.

The comparative statistics imply that biodiesel tends to be denser, more viscous, and safer for handling because it has a much higher flash point than petroleum diesel. These characteristics will affect fuel injection, combustion performance, and requirements for storage. The increased viscosity and density of biodiesel should have some effects on engine operation but in a positive way upon lubrication and its high flash point provides superior safety during transport and storage. Generally, biodiesel characteristics render it an environmentally and operationally safer option compared to regular diesel

1.7 SIGNIFICANCE OF THE STUDY

The potential to address environmental concerns surrounding the disposal of used cooking oil and the growing need for renewable energy sources makes this work noteworthy. The project will look at a new and efficient method for creating biodiesel from a commonly available waste product by trans esterifying wasted cooking oil using zinc-doped calcium oxide catalysts. This will help to valorize waste and lessen traditional dependency on fossil fuels. Using cutting-edge methods like XRD, and GC-MS to characterize the catalyst and biodiesel guarantees that the materials and fuel properties are understood, which is essential for manufacturing process optimization. With the worldwide goals of renewable energy and environmental safety, it will help to increase the use of waste oil and the sustainability of biodiesel production, offering a cleaner fuel substitute.

1.8. NEED AND SCOPE OF THE STUDY

Such a study will become necessary as the requirement for using sustainable and renewable energy sources grows and the disposal of used cooking oil becomes more environmentally sensitive. Therefore, using a transesterification reaction to turn used cooking oil into biodiesel offers a viable alternative method of reducing waste while producing a substitute fuel to lessen the environmental risk associated with fossil fuels. In the case study of production, it aims to synthesize, describe, and apply a biodiesel made from leftover cooking oil and methanol based on calcium oxide impregnated and doped with a small amount of zinc for oxidation activity. Critical information on production efficiency, fuel optimization conditions, and providing better quality of biofuel for emissions reduction will be provided by the study. Enhancing the production cost, minimizing the environmental effect of traditional diesel fuels, and maximizing the generation of biodiesel from waste oils are all benefits of this research.

1.9. STATEMENT OF THE PROBLEM

A sustainable answer to waste management and the rising need for alternative fuels will be provided by the transesterification reaction, which will turn used cooking oil into biodiesel. Nevertheless, the efficacy of the procedure will rely on the catalyst employed in the reaction. This study will prepare and characterize a zinc-doped calcium oxide catalyst made by wet impregnation to increase biodiesel yield and efficiency. The catalyst will be examined with X-ray diffraction (XRD) for the purpose of characterizing its structure and composition. Using a specially prepared catalyst, methanol and used cooking oil were trans-esterified. GC-MS spectroscopy will also be used to characterize the biodiesel after determining its chemical composition. Routine testing would be used to evaluate the fuel qualities of biodiesel at the Bundelkhand university Jhansi (innovation center Lab).

1.10. RESEARCH OBJECTIVES

The objectives of this study are:

- Collection of WCO sample from different sources.
- Improving the Transesterification reaction conditions to high biodiesel yield and quality by physicochemical fuel properties analysis.
- To use X-ray diffractometer (XRD) to develop and characterize Zinc-doped Calcium oxide (CaO) by the wet impregnation method.
- To use the produced catalyst and methanol to create biodiesel from spent cooking oil, then use Gas Chromatograph-Mass Spectrophotometer (GS-MS) to describe it.
- To develop efficient production process by minimising energy consumption and reducing production cost.
- To investigate a better alternative feed stock for biodiesel production.

REVIEW OF LITERATURE

Bhatia et al. (2020) investigated the use of a heterogeneous catalyst made from cork charcoal to convert used cooking oil into biodiesel [26]. The study emphasized the sustainable utilization of waste resources for the production of biofuels. Their primary objective was to improve the yield and effectiveness of biodiesel production by optimizing reaction parameters like temperature, reaction time, and catalyst concentration. They concluded that cork biochar was a viable substitute for conventional catalysts due to its remarkable catalytic properties, which included a high surface area, thermal stability, and reusability. The study also highlighted the advantages using biochar-based catalysts offers for the environment. In addition to lowering reliance on non-renewable catalysts, these catalysts helped sequester carbon and convert waste into useful goods. Furthermore, by comparing the performance of cork biochar to that of other synthetic and bio-based catalysts, the researchers discovered that it is more active and long-lasting. According to their research findings, it is economically feasible to use biochar-based catalysts in the production of biodiesel. This opens the door for more economical and ecologically beneficial biofuel technologies.

Khodadadi et al. (2020) conducted a comprehensive investigation of the most recent advancements in the catalytic conversion of used cooking oil, with an emphasis on the substance's potential as a sustainable feedstock for the production of biofuels [27]. Enzymatic, homogeneous, and heterogeneous catalysis were among the catalytic processes that were the subject of this investigation. Special attention was paid to these procedures' effectiveness, reaction mechanisms, and applications in the real world. The authors examined the role that enhanced catalysts, such as metal-based and nanostructured materials, play in enhancing reaction speeds, selectivity, and total yield while addressing a number of important issues, such as catalyst deactivation, energy requirements, and feedstock unpredictability. The report also emphasized the advantages of biofuels made from used cooking oil in terms of money and the environment. The change may lessen reliance on fossil fuels, reduce emissions of greenhouse gases, and encourage waste valorization, according to the report. In order to improve the scalability and cost-effectiveness of catalytic conversion techniques, the study also looked into process optimizations and technology developments. By assessing the current constraints and possible future research routes, the authors offered valuable insights into the feasibility and sustainability of waste cooking oil as a renewable energy source.

Haq et al. (2021) examined the possibility of using leftover cooking oil for the esterification and transesterification processes to produce biodiesel [28]. It evaluated these oils' viscosity, free fatty acid content, and total fatty acid composition, among other physicochemical characteristics. In order to ascertain their influence on the production and quality of biodiesel, the researchers additionally looked into variables like alcohol to oil molarity, catalyst concentration, reaction time, and reaction temperature. According to the study, pre-treatment techniques greatly enhanced the conversion process, and the transesterification process's efficiency varied based on the waste oil employed. An additional esterification step was required for oils with a lot of free fatty acids. According to the study, biodiesel made from spent cooking oils is a viable and environmentally friendly substitute for conventional fossil fuels since it satisfies the necessary fuel requirements when reaction conditions are enhanced. Additionally, the study emphasized the financial and environmental benefits of recycling used cooking oils, which may help alleviate issues with waste management and promote the production of renewable energy. Waste cooking oils can be used as a sustainable feedstock for large-scale biodiesel production, which would help protect the environment and energy supply, according to the authors' findings.

Hsiao et al. (2020) investigated how to use a modified calcium oxide catalyst in a microwave heating system to get the most out of the biodiesel produced from used cooking oil [29]. By altering calcium oxide's catalytic properties, the transesterification process would be enhanced and biodiesel production would rise. The temperature, processing time, molar ratio of methanol to oil, and catalyst concentration were the primary focus of the investigation. The findings demonstrated that, in contrast to more conventional methods, microwave-assisted heating significantly increased reaction rate, slashed processing time and energy consumption, and maintained a high biodiesel yield. The stability and reusability of the modified catalyst were further investigated, proving its efficacy across a range of reaction cycles. The study demonstrated that modified calcium oxide has the potential to support the repurposing of used cooking oil and the production of sustainable biodiesel as a catalyst that is cost-effective, environmentally friendly, and highly effective.

Suzihaque et al. (2022) investigated the process of turning used cooking oil into biodiesel, emphasizing its potential as an economical and ecologically responsible substitute for fossil fuels [30]. It investigates the effects of several transesterification techniques on the yield and quality of biodiesel, including enzymatic procedures and homogeneous and heterogeneous catalysts. In order to increase production effectiveness, the study highlights how crucial it is to

modify reaction parameters including temperature, alcohol-to-oil ratio, and catalyst concentration. The report also emphasizes the financial and ecological advantages of recycling spent cooking oil, which not only lessens disposal problems but also supports the sustainability of renewable energy. The authors do, however, recognize difficulties with catalyst deactivation, feedstock irregularities, and effective purifying techniques. Additionally, they talk about developments in biodiesel processing that could increase reaction rates and fuel conversion efficiency, like Nano catalysts and ultrasonic-assisted technologies. The study opens the door for more research to improve the feasibility and scalability of the process by offering insightful information on technological developments and constraints in the manufacture of biodiesel.

Sulaiman et al. (2020) finished a thorough study on the transesterification process of producing biodiesel from refined used cooking oil using co-metal oxide catalysts [31]. The goal of the research project was to overcome the challenges associated with the production of biodiesel. These difficulties include the need for effective catalysts and the high cost of raw ingredients. The researchers found that co-metal oxide catalysts, which were created by mixing two different metal oxides, had better catalytic qualities than single-metal catalysts. Among these qualities were enhanced stability and activity. In order to optimize the transesterification process and ultimately create more biodiesel overall, their investigation revealed that reaction parameters including temperature, catalyst concentration, and oil-to-methanol molar ratio were crucial. The study also emphasized the financial and environmental advantages of recycling this resource by using refined used cooking oil, a waste product, to produce biodiesel. The results demonstrated how co-metal oxide catalysis has the potential to boost biodiesel production while also assisting in its sustainable and economical production. As a result, it has emerged as a viable method for simultaneously reducing waste and meeting energy needs.

Pauline et al. (2021) examined the kinetics of transesterification and the performance of waste cooking oil in diesel engines [32]. Waste cooking oil is converted into biodiesel with the use of a catalyst and alcohol, usually methanol from the food preparation sector. The researchers focused on improving temperature, catalyst concentration, and reaction time to increase biodiesel production. According to the study, under ideal circumstances, the transesterification process produced biodiesel at a high rate from used cooking oil. Additionally, the biodiesel's fuel qualities, such as its cetane number, calorific value, and viscosity, were evaluated. The biodiesel ran well in a diesel engine with emissions and fuel economy comparable to regular diesel. The study says that used cooking oil can be a sustainable feedstock for making biodiesel. This makes it a viable alternative to traditional fossil fuels and helps make greener energy

sources. It also encourages ongoing research into renewable fuels in order to reduce reliance on petroleum-based products that are not renewable.

Hassan and Smith (2020) examined in order to improve its efficiency and environmental friendliness, a study examined the microwave-assisted transesterification method for converting used cooking oil into biodiesel [33]. By considering variables like catalyst concentration, reaction duration, and microwave power, the researchers were able to optimize the procedure. According to the findings, microwave irradiation accelerated the transesterification reaction, which increased energy efficiency and produced biodiesel more quickly. Higher biodiesel yields in less time were made possible by the technique, which also reduced energy use. This demonstrates how leftover cooking oil can be used as an inexpensive and sustainable feedstock, reducing environmental waste and offering a substitute for energy sources that rely on fossil fuels. According to the study's findings, this ground-breaking technology might significantly enhance sustainable biodiesel production techniques and provide a competitive substitute for the production of renewable energy from garbage.

Supraja, Behera, and Paramasivan (2020) investigated the potential for increasing biodiesel production efficiency by process variable optimization in the two-step microwave-assisted transesterification of used cooking oil [34]. The researchers discovered significant characteristics that have a direct impact on the quantity and quality of biodiesel produced. Some of these variables include temperature, catalyst concentration, and reaction time. They employed a methodical approach to optimize these parts with the intention of increasing the reaction rate while simultaneously reducing the amount of energy required. By significantly shortening reaction times and increasing biodiesel yields, their findings demonstrated that the microwave-assisted transesterification process outperformed conventional approaches. Additionally, the study emphasized the significance of utilized cooking oil as a sustainable fuel for the production of biodiesel. Additionally, it demonstrated how this feedstock may help create sustainable energy sources and lessen pollution in the environment at the same time. The results not only shed light on the efficiency of microwave-assisted transesterification but also offered a more economical and ecologically friendly substitute for conventional biodiesel production methods.

Pugazhendhi et al. (2020) studied on the manufacturing of sustainable biodiesel from used cooking oil with an emphasis on India, biodiesel output can be increased by modifying process factors such reaction temperature, catalyst concentration, and reaction duration [35]. To comprehend the reaction mechanisms and identify the best circumstances for the production of

biodiesel, the researchers employed kinetic and thermodynamic studies. According to the study, modifying process factors greatly improves the sustainability and efficiency of biodiesel production. The process's potential for economic viability under optimal circumstances was shown by an investigation into its thermodynamic feasibility. The study also addressed the disposal issues related to waste oils and demonstrated the environmental advantages of using used cooking oil as a feedstock, offering a sustainable substitute for conventional diesel. This helps India create a biodiesel production process that is more economical, ecologically friendly, and sustainable.

Zhao et al. (2021) detailed China has conducted a comprehensive investigation into the biodiesel production process from used cooking oil. The study examined the process's economic viability as well as the environmental effects of this conversion [36]. Compared to conventional diesel, it has been demonstrated that using used cooking oil as a feedstock for biodiesel has significant advantages for the environment, including a reduction in greenhouse gas emissions, the use of landfills, and issues with waste disposal. These benefits were emphasized in the research. The study also looked at the process's economic viability, paying close attention to important factors like the demand for biodiesel in the market, the availability of feedstock, production costs, and advancements in technology. The authors discovered that, in the long run, it might be financially viable to convert used cooking oil into biodiesel if the government enacted the necessary regulations and offered incentives. This is true despite the difficulties posed by the need for more efficient conversion technologies and the fluctuating costs of collecting waste oil. They also talked about how this approach could help China meet its goals for renewable energy, reduce its reliance on foreign oil, and encourage a circular economy. As a consequence of this, they presented used cooking oil as a useful resource for the biodiesel industry in the nation.

Safaripour et al. (2024) investigated the production of biodiesel from waste vegetable cooking oil using catalysts with a LaNi1-xCoxO3 perovskite structure [37]. The study intends to tackle problems pertaining to renewable energy and waste management. When compared to conventional catalysts, the researchers discovered that these catalysts shown notable gains in catalytic activity, selectivity, and stability. The study also emphasized the significance of the catalyst's metal composition, particularly Ni and Co. Because of their enhanced surface characteristics and increased stability at higher temperatures, some compositions demonstrated better performance. The study also highlighted the role that vegetable oil waste plays in the creation of environmentally friendly biofuels and the economic and environmental benefits of

using it as a feedstock. This study adds to the growing body of research on perovskite catalysts and their use in the production of biodiesel by providing a sustainable alternative to fossil fuels and addressing the environmental effects of waste oil disposal.

Kumar et al. (2020) used leftover cooking oil and chicken fat oil as feedstocks, researchers have created a unique process for making biodiesel [38]. Environmental concerns and the rising need for renewable energy sources were the focus of the study. Waste oils were transformed into methyl esters via transesterification and simultaneous esterification using an acid catalyst. Conventional base-catalyzed techniques are challenging due to the high amount of (FFA) in waste oils. FFAs were successfully converted into biodiesel using a combination of the esterification and transesterification processes. This integrated strategy improved the process's economic viability and environmental friendliness while increasing the production of methyl esters. This provided an alternate renewable energy source and helped with waste management. The work opened the door for scalable applications in the biodiesel sector and increased the efficiency of producing biodiesel from inexpensive and inedible feedstocks.

Mateos et al. (2021) examined the bio-catalytic hydrolysis, esterification, and transesterification of used cooking oil using vegetable lipase [39]. The purpose of this study was to clarify the potential of enzyme-catalyzed processes for the production of environmentally friendly biofuels. They raised awareness of the significance of making use of used cooking oil, a cheap and abundant resource, as a feedstock for the production of biofuels through their research. Compared to conventional fossil fuels, this is a choice that is better for the environment. The authors also highlighted how well vegetable lipases work as catalysts for these processes. Triglycerides are broken down by hydrolysis into glycerol and free fatty acids, biodiesel is produced by esterification, and the process is further optimized for higher yields by transesterification. Their study's findings demonstrated the advantages of bio catalysis over conventional chemical methods, including improved selectivity, less harsh reaction conditions, and minimal environmental impact. The study significantly advanced the current initiatives to lessen dependency on non-renewable energy sources and encourage circular economy practices. The study also provided information on how to make enzyme-based biodiesel manufacturing more economical and efficient. By demonstrating the feasibility of using used cooking oil as a renewable resource for biofuels, this was achieved.

Goh et al. (2020) emphasized the potential of WCO as a clean, sustainable substitute for conventional fossil fuels [40]. With an emphasis on transesterification and enhanced catalytic processes, the authors examined several conversion methods for turning WCO into premium

biodiesel and bio jet fuel. In order to increase productivity and lower energy consumption, they also investigated cutting-edge techniques like supercritical fluid processing and enzyme-catalyzed processes. The study also looked at issues with WCO feedstock, like impurities, moisture content, and free fatty acids, which can have an impact on the final product's production and quality. Pre-treatment procedures and the creation of innovative catalysts are examples of solutions. The research highlights the significance of sustainable methods for cost-effectiveness and scalability in the manufacture of bio jet fuel and WCO-based biodiesel. With its emphasis on WCO's function in waste reduction, greenhouse gas emission reduction, and circular economy promotion, the study makes a substantial contribution to our understanding of WCO as a renewable resource for the clean energy industry.

Ahmed et al. (2023) examined the simulation and optimization of producing biodiesel from used cooking oil using a supercritical transesterification reaction without a catalyst [41]. One of the many issues that traditional biodiesel production methods face is the high cost and negative impact on the environment caused by the use of catalysts. The goal of this investigation was to find solutions to these issues. The researchers were able to thoroughly examine the connection between the yield of biodiesel and a number of other process variables, including temperature, pressure, and reaction time, by employing a simulation model. According to the findings of their study, supercritical transesterification is a more environmentally friendly and effective alternative to conventional treatment methods for the conversion of used cooking oil into biodiesel. The process's lack of catalysts not only reduced operating costs but also made it possible for the production of biodiesel to have a less negative environmental impact. The study also showed that this method could be extended for use in industrial settings, which would encourage the sustainable use of spent oils as a raw material for biodiesel production. The shift to energy sources that are better for the environment was aided by significant advancements in the efficiency of biodiesel synthesis.

Zhang et al. (2023) investigated by transesterifying used cooking oil using a molybdenum (Mo) catalyst backed by graphitic carbon nitride (g-C3N4), the study investigates a unique approach to biodiesel production [42]. The g-C3N4-Mo catalyst was shown to have good stability, catalytic activity, and surface area, which led to a higher transesterification reaction efficiency. The effects of temperature, catalyst concentration, and reaction time on the synthesis of biodiesel were also investigated in the study. The remarkable reusability of the g-C3N4-Mo catalyst made it a viable choice for widespread application. The study also emphasized how crucial it is to use used cooking oil as a substitute feedstock in order to lessen

environmental impact and advance the circular economy. The results demonstrate the potential of catalytic materials like g-C3N4-Mo in sustainable energy processes and offer important insights into creating more economical, ecologically friendly, and efficient biodiesel production techniques.

Li et al. (2021) investigated the utilization of environmentally friendly nanoparticle catalysts for the co-transesterification of algal oil, waste cooking oil, and dimethyl carbonate (DMC) [43]. The research aims to control garbage and produce renewable energy. The study makes use of DMC, a methylating agent that is good for the environment, as well as feedstocks that are easy to find and cheap, like algae oil and old cooking oil. Utilizing nanoparticle catalysts has numerous advantages, including increased stability, increased catalytic activity, and the capacity to drive transesterification processes at lower temperatures and pressures. The study found that this method yields pure, high-yield biodiesel and beneficial by-products, demonstrating its long-term viability. In addition, the study emphasized the possibility of using waste oils as feedstocks for the production of biodiesel, which would reduce dependence on food production, reduce waste, and encourage the circular economy. The study contributes to the development of eco-friendly and efficient biodiesel production methods, which have the potential to reduce greenhouse gas emissions and boost the economic viability of alternative energy sources.

Foo et al. (2022) investigated the process of turning WCO into useful goods is examined in this paper, with an emphasis on different strategies and how they might be applied to waste management that is environmentally responsible [44]. Important procedures include pyrolysis to produce bio-oil and transesterification to produce biodiesel. It has been investigated how bioconversion techniques employing microorganisms and enzymes can boost product yields while lessening their negative effects on the environment. Nonetheless, issues including impurities, varying oil quality, and effective purification techniques are emphasized. In order to increase productivity and product diversity, the study also highlights the significance of creating technologies such as enzymatic catalysis and integrated systems that combine several conversion methods. In order to solve these problems and maximize the technological and financial benefits of WCO recycling, the researchers stress the necessity for additional study. In order to support the economic viability of WCO conversion processes, especially in the generation of renewable energy and sustainable waste management, they emphasize the necessity of scalability and cost reduction in their conclusion.

Guo et al. (2022) conducted according to a study; waste cooking oil can be trans esterified into biodiesel using CuO/ZnO as a photocatalyst [45]. The catalyst proved to be an environmentally friendly method of producing biodiesel due to its exceptional recyclability and high catalytic effectiveness. The study also looked at how the synthesis of biodiesel was affected by variables such reaction temperature, catalyst concentration, and reaction time. The outcomes reveal methods for maximizing process efficiency. A thorough grasp of the reaction mechanism was obtained by analyzing the transesterification reaction's kinetics as well. By utilizing used cooking oil, CuO/ZnO could, according to the study, significantly reduce the environmental impact of producing biodiesel while also promoting renewable energy sources and waste management. This study supports the use of used cooking oil as a feasible feedstock for renewable energy sources and advances the development of economical and environmentally friendly catalytic devices for the synthesis of biodiesel.

Paladino and Neviani (2021) utilized in order to create environmentally friendly biodiesel, researchers have looked into using waste cooking oil in the transesterification process [46]. Additionally, they investigated the possibility of feeding microalgae with wastewater containing glycerol, a by-product of biodiesel production. Because microalgae are known for their rapid growth and use of organic compounds, this is a sustainable method of getting rid of glycerol. The possibility of increasing the production of microalgal biomass for the production of biofuel was also emphasized in the study. In accordance with the concepts of a circular economy, this strategy emphasizes waste valorization and the production of renewable energy to reduce the environmental impact of biodiesel production and wastewater disposal. By indicating that adding microalgae to the biodiesel production cycle might optimize resource use and minimize waste, the research made a substantial contribution to the development of more environmentally friendly biodiesel manufacturing techniques.

Hosseinzadeh-Bandbafha et al. (2022) investigated the use of green catalysts as a sustainable substitute for conventional catalysts in the treatment of hazardous waste cooking oil [47]. The authors draw attention to the growing demand for environmentally friendly waste management techniques because of the growing amount of used cooking oil. They investigate different methods for turning this trash into biofuels, concentrating on biodiesel as a substitute energy source. The study emphasizes how crucial it is to adjust these catalysts for increased yield and sustainability, paying particular attention to crucial aspects like stability, reusability, and selectivity. The study also highlights how this approach helps the environment by lowering hazardous waste and fostering a circular economy. In order to reduce waste and generate

renewable energy, the review offers insightful information about the possibilities for bioenergy production using used cooking oil and green catalysts.

Elouahed et al. (2024) optimized a Mo7-Zn3/CaO catalyst for trans esterifying used cooking oil into biodiesel using RSM. The authors addressed the economic and environmental concerns related to the manufacture of biodiesel by concentrating on an effective catalyst, waste cooking oil, and a sustainable feedstock [48]. To ascertain the ideal circumstances for the Mo7-Zn3/CaO catalyst to attain the maximum transesterification efficiency, they experimented with a number of variables, such as temperature, reaction time, catalyst concentration, and methanol-to-oil ratio. This increased the production rates of biodiesel in comparison to conventional catalysts. The catalyst's extensive surface area and active sites greatly aided the conversion process. The study also emphasized the potential of used cooking oil as an economical and sustainable feedstock for the manufacturing of biodiesel, providing a viable way to reduce waste and support sustainable energy sources. By providing insights into sophisticated catalytic systems and process optimization techniques for boosting biodiesel production, this study made a substantial contribution to waste-to-energy and renewable energy technology.

Shaban et al. (2020) investigated Zinc aluminate nanoparticles' production, characterization, and application as a catalyst for the conversion of used cooking oil into biodiesel have all been the subject of research [49]. The structure, morphology, and surface functional groups of the nanoparticles were assessed by researchers using Fourier transform infrared spectroscopy, scanning electron microscopy, and X-ray diffraction. The results showed a lot of crystallinities, a uniform size distribution, and a strong catalytic potential. The study emphasized the importance of using used cooking oil as a feedstock for recycling waste and providing a cost-effective and environmentally friendly method for producing biodiesel. The nanoparticles displayed remarkable durability, reusability, and catalytic efficacy during the transesterification process. These nanoparticles have the potential to greatly boost biodiesel production, lower production costs, and aid in the creation of renewable energy sources. This study provides an environmentally friendly method for converting waste oil and increases the sustainability of energy use.

Foroutan et al. (2020) studied a new Nano catalyst (CaO@MgO) has been created in a study to enhance the production of biodiesel from waste edible oils [50]. The composite Nano catalyst solves common biodiesel synthesis problems like partial conversion and low reaction rates. The generation of biodiesel and reaction speed were both increased by the CaO@MgO

Nano catalyst's strong catalytic activity. By providing a less expensive option to conventional biodiesel sources and reducing waste, the authors highlight the financial and environmental advantages of employing waste food oils as feedstock. By optimizing biodiesel production, the improved Nano catalysts offer a more environmentally friendly method of biofuel synthesis. By offering new perspectives on the use of nanotechnology for efficient and ecologically friendly biofuels, this work adds to the expanding body of research on the manufacture of biodiesel from renewable resources. The results support the economic viability of biofuels and ecological sustainability, and they are especially pertinent to the production of biodiesel on a big scale.

Costa et al. (2020) investigated the possibility of using old cooking oil as a feedstock for the enzymatic biodiesel-making process known as hydro esterification [51]. The objective of this study was to investigate a novel and environmentally friendly method for producing biodiesel from waste oils, which are plentiful and typically discarded, with the intention of reducing waste. This article discusses the advantages of using enzymatic catalysts over conventional chemical methods. Reduced energy consumption, a reduced production of harmful by-products, and the capacity to operate in more hospitable conditions (such as lower pressures and temperatures) are among these advantages. The essay goes into great detail about these advantages. The study's goal of raising biodiesel yields was accomplished. The process parameters that were optimized to achieve this included enzyme concentration, reaction time, and temperature. Additionally, the study emphasized the environmental benefits of using used cooking oil as a source of renewable energy and a solution to the issue of waste oil disposal. This is consistent with the growing demand for more circular and ecologically friendly manufacturing processes. By supporting an integrated approach to waste valuation and sustainable energy production, respectively, Costa and colleagues' study significantly advanced the area of biofuels.

Zhang et al. (2022) discovered a catalytic system supported by molybdenum (Mo) on the outer surface of the zeolite material ZSM-22 has been used to develop a new biodiesel production process [52]. In order to overcome the financial and environmental issues related to traditional techniques, the researchers enhanced the catalyst's performance to attain high conversion rates of waste oils into biodiesel. By adjusting reaction parameters including temperature, catalyst loading, and the methanol-to-oil ratio, the Mo/ZSM-22 catalyst demonstrated notable increases in yield and cost-effectiveness. Mo was added to ZSM-22's outer surface to promote catalytic activity, which sped up and improved the transesterification process. This approach supports

sustainable energy goals by providing a low-cost and eco-friendly biodiesel manufacturing alternative in addition to helping with trash recycling. The discovery provides an effective, economical, and ecologically friendly catalytic solution, opening up new avenues for the manufacture of biodiesel on a wide scale, especially from waste oils.

Patchimpet et al. (2020) studied was to use lipase from Nile tilapia viscera to trans esterify used cooking oil in order to maximize the production of biodiesel [53]. The researchers focused on important variables like temperature, reaction time, enzyme concentration, and oil-to-methanol ratio in order to determine the ideal conditions for the production of biodiesel. The effective catalytic activity of the lipase found in the viscera of Nile tilapia enabled it to produce high rates of biodiesel from discarded cooking oil. Utilizing fish viscera, a by-product of the fish industry, provided a sustainable alternative for the production of biodiesel in addition to reducing waste. The study also shown the potential of employing inexpensive, locally accessible biological catalysts as a substitute for traditional chemical catalysts, opening the door to the production of renewable energy that is both economically and environmentally feasible. In response to rising worldwide energy demands and environmental concerns, the research also created new avenues for combining waste recycling and sustainable bioenergy solutions.

Majamo, Amibo, and Bedru (2023) investigated the creation and use of a biomass-derived magnetic biochar catalyst to encourage the simultaneous esterification and transesterification of used cooking oil into biodiesel [54]. The researchers focused their efforts on developing a catalyst that enhances biodiesel production while also utilizing waste biomass, so making the process more environmentally friendly. They were able to get a high biodiesel yield while lowering the energy and possibly hazardous chemicals used by predicting the catalytic performance and optimizing the reaction conditions. By adding magnetic properties to the biochar, the catalyst made it simple to separate and repurpose the biochar, further increasing the process's environmental friendliness. Their research revealed the potential for using used cooking oil as a feedstock for biodiesel production, which would promote waste recycling and lessen the environmental impact of the biodiesel production process. The study's overall approach, which integrates waste management, catalyst innovation, and optimization techniques, significantly advances sustainable biofuels and green energy solutions.

Outili et al. (2020) improved the environmental and financial viability of producing biodiesel from used cooking oil; the study focuses on enhancing this process by employing green chemistry techniques [55]. The authors recognize the potential of used cooking oil as a good

feedstock for biodiesel as well as the growing significance of renewable energy sources. With an emphasis on optimizing the transesterification reaction, they look into several ways to enhance the biodiesel production process. In order to assess the process's environmental impact and make sure that biodiesel production was both efficient and sustainable, green chemistry measures were implemented. According to the study, waste cooking oil might produce significant amounts of biodiesel with little harm to the environment, so advancing the objectives of green chemistry and the production of renewable energy. This study highlights the significance of applying green chemistry concepts to industrial processes in order to balance energy production with environmental preservation, and it adds to the continuous attempts to identify sustainable substitutes for traditional fuels.

Mohamed et al. (2020) studied the use of a high-operative heterogeneous catalyst to produce biodiesel from used cooking oil [56]. Managing trash and meeting electricity demand in this way is sustainable. To boost biodiesel synthesis's output and effectiveness, the authors focused on enhancing the catalytic process through a variety of methods. They discovered that the heterogeneous catalyst performed better than conventional approaches, particularly in terms of reusability, stability, and catalytic activity. As a result, it can be used in place of large-scale biodiesel production. The study's conclusions indicate that using used cooking oil as a feedstock has several advantages for the economy and the environment. This approach aids in the production of renewable energy in addition to reducing waste. The scientists also said that the method is good for the environment because it doesn't need expensive feedstocks that use a lot of resources. In turn, this encourages a more cost-effective and long-lasting method of producing biodiesel. The study's findings provided significant new information regarding the biodiesel production potential of heterogeneous catalysts. Additionally, these results demonstrated that these catalysts may be crucial to the development of biofuels in the future.

Ataei, Karbasi, and Baghdadi (2023) conducted the use of MgO/oxidized g-C2N2 nanocatalysts to turn used cooking oil into biodiesel has been studied. By oxidizing g-C2N2, a carbon nitride material, the researchers enhanced its catalytic properties when combined with magnesium oxide [57]. The findings demonstrated notable improvements in the catalytic activity of the Nano catalyst, including higher stability and conversion efficiency. Overall catalytic activity was increased by the increased interaction with MgO made possible by the oxidized g-C2N2. This is essential for the production of sustainable biodiesel. The study offers guidance for developing catalytic systems that are more economical, ecologically friendly, and efficient. It also emphasizes how leftover cooking oil may be used as a sustainable feedstock

to produce biodiesel. The study highlights how crucial catalyst stability and reusability are to the sustainability and economic feasibility of biodiesel synthesis techniques for industrial use.

Mohiddin et al. (2024) investigated in order to trans esterify wasted cooking oil, researchers have created a magnetic biochar catalyst using palm lignocellulosic biomass [58]. Significant catalytic activity was shown by the catalyst, which makes it a cost-effective and ecologically beneficial choice. To ascertain their effect on the synthesis of biodiesel, the researchers also looked at important process variables like temperature, catalyst concentration, and reaction duration. The catalyst's stability and reusability allowed the improved process to produce notable biodiesel conversion rates. By exposing the reaction sequence and activation energy, the kinetic analysis also improved our comprehension of the reaction mechanism. This study emphasizes how waste biomass materials, especially palm lignocellulosic biomass, can be used to address environmental issues brought on by spent cooking oils and produce renewable energy sources like biodiesel. The study emphasizes how waste biomass materials, especially palm lignocellulosic biomass, can be used to produce biodiesel.

Thilakarathne et al. (2021) presented the manufacture of biodiesel from used cooking oil has been studied, with an emphasis on laboratory-scale processes and the variables that affect the product's yield and quality [59]. The transesterification process, which is frequently used to turn spent cooking oil into biodiesel, was studied by the authors. They emphasized how important it is to use the right catalyst, acidic or alkaline, to make the reaction work as well as possible. The transesterification procedure was also examined in relation to the reaction temperature, time, and oil-to-methanol ratio. The study says that using used cooking oil as a feedstock has a lot going for it, like less waste, lower production costs, and being better for the environment than traditional biodiesel feedstocks. However, the scientists also pointed out the disadvantages of using used cooking oil, such as the inconsistent quality, high content of free fatty acids, and need for efficient pretreatment methods. They also emphasized that effective purification techniques and lower manufacturing costs are required for the process to be economically viable on a broader scale.

Bai et al. (2022) improved the quality of biodiesel made from spent oils; the research study concentrated on optimizing the esterification process for deacidifying waste cooking oil [60]. The (RSM) was used to evaluate the effect of various process variables on the esterification reaction, enabling the selection of optimal parameters such as temperature, reaction time, catalyst concentration, and oil-to-alcohol ratio. Additionally, investigated were the use of solvents and ultrasonic assistance, which boosted the deacidification process's overall efficacy

and rate of reaction. Because ultrasonic waves were able to speed up reaction times and improve the overall efficacy of the deacidification process, higher-grade biodiesel was produced. The use of solvents made the reaction more effective and also made the reactants more soluble. This strategy for producing biodiesel on a large scale is feasible because it was demonstrated to be particularly effective in enhancing the deacidification of used cooking oil. Bai and colleagues' research significantly advanced the manufacturing of biofuel by putting forth a practical and sustainable process for turning used cooking oil into biodiesel, which might lessen the impact on the environment and promote the use of renewable energy sources.

Abu-Ghazala et al. (2023) examined the efficient catalytic transesterification of used cooking oil into biodiesel at room temperature using a K2CO3/-Al2O3 Nano-catalyst [61]. Because it tackles environmental issues and the depletion of fossil fuels, this research represents a significant advancement in the manufacturing of biodiesel. Because it is renewable and works with current diesel engines, biodiesel is a possible substitute. High reaction temperatures, which can be expensive and energy-intensive, were necessary in the past. However, the authors' method significantly lowers energy usage and operating expenses by using a safe, eco-friendly K2CO3/γ-Al2O3 Nano-catalyst. The study expands on earlier investigations on solid catalysts, which have benefits in terms of environmental impact and reusability. Because of its high catalytic efficiency, stability, and reusability, the K2CO3/γ-Al2O3 catalyst is a good choice for producing biodiesel. The work adds to the expanding corpus of research that aims to create economical and sustainable biodiesel production techniques, which could help with waste management and the generation of renewable energy while facilitating the world's shift to cleaner energy sources.

Liu et al. (2021) simulated the production process and performed an economic analysis for the generation of biodiesel from used cooking oil [62]. Cooking oil waste is a sustainable feedstock that can meet the demands of renewable energy and trash management. The complete process was modelled in the study, considering operating costs, energy consumption, and raw material costs. The researchers discovered that waste cooking oil solves waste disposal problems and is more affordable than more conventional sources like vegetable oils. Increasing the efficiency of the catalyst and lowering energy usage are two ways to optimize the production process, which could lower costs and boost the output of biodiesel. The scalability of this approach was also emphasized by the authors, who hypothesized that large-scale production may further reduce expenses and boost resource efficiency. By lowering greenhouse gas emissions and encouraging waste-to-energy initiatives, the study not only shows the commercial viability of

using spent cooking oil to produce biodiesel but also advances sustainable energy production. This discovery provides a workable answer to the problems of waste management and renewable energy while also being consistent with the concepts of green chemistry.

Naeem et al. (2021) used a one-of-a-kind bio-based bi-functional catalyst to make biodiesel from highly acidic waste cooking oil [63]. The high acidity of used cooking oils, which frequently contain free fatty acids, makes biodiesel production challenging. Traditional approaches like transesterification make it difficult to work with these oils, necessitating additional pre-treatment procedures. The researchers developed a bi-functional catalyst with acidic and basic sites to circumvent this issue. This allowed for the simultaneous transesterification of triglycerides and the esterification of free fatty acids in a single reaction step. This dual function resulted in greater reaction efficiency and higher biodiesel yields than previous methods. The bio-based catalyst showed exceptional catalytic activity and extraordinary stability, both of which are necessary for the long-term production of biodiesel. The study also emphasized the financial and environmental advantages of using used cooking oil as a raw material to make biodiesel. The results of this study demonstrate how bio-based catalysts might enhance the processes used to produce biodiesel, offering a cost-effective and environmentally friendly substitute for traditional catalytic systems.

Liu et al. (2024) increased the production efficiency of biodiesel by converting waste cooking oil into biodiesel using a high-efficiency beta-zeolitic catalyst [64]. The study emphasized the difficulties faced by catalytic processes, such as poor conversion rates and catalyst deactivation, as well as the growing interest in ecologically appropriate substitutes for conventional fossil fuels. To get over these limitations and offer a more economical and ecologically beneficial way to produce biodiesel, the beta-zeolitic catalyst was created. To guarantee the maximum amount of biodiesel, the researchers looked into a number of reaction factors, including temperature, catalyst loading, and oil-to-methanol ratios. The study backs up earlier findings that emphasize how crucial it is to improve catalyst performance in order to enable the broader use of waste oils for the creation of biofuel. The study also contributes to the body of knowledge regarding alternative fuel sources by demonstrating the potential of waste cooking oil as a renewable feedstock to address energy and environmental issues.

Maleki et al. (2023) investigated the possibility of using walnut shell and sawdust as low-cost, long-lasting catalysts for the production of biodiesel from used cooking oil [65]. The study used RSM and Artificial Neural Networks (ANN) to improve the production efficiency of biodiesel. The study emphasized the increased interest in resource recycling using waste

materials like sawdust and walnut shell, as well as ecologically friendly chemistry. The output of biodiesel increased as a result of these materials' optimization, which also showed promise for increasing process efficiency. The results highlight how crucial it is to use affordable and renewable resources for environmentally benign and financially viable biodiesel manufacturing techniques. By highlighting the significance of material selection and strategy optimization to obtain higher biodiesel yields while limiting environmental impact, the research adds to the body of knowledge on sustainable biodiesel production.

Razuki et al. (2023) focused on bismuth ferrite Nano catalysts to create a more efficient and eco-friendly method of manufacturing biodiesel [66]. The manufacture of biodiesel advanced significantly as a result of the introduction of these Nano catalysts for the transesterification of waste cooking oil and palm oil. These Nano catalysts were synthesized and characterized by the researchers, and their higher biodiesel yield, lower reaction temperatures, and increased stability made them appropriate for large-scale biodiesel production. The Nano catalyst also helps to meet the increasing need for renewable energy sources globally and helps to repurpose wasted cooking oils. In order to improve catalyst reusability and optimize reaction conditions, the researchers built on earlier studies on different Nano catalysts appropriate for biodiesel production. The low toxicity and potential to lower the carbon footprint of the biodiesel production process are two advantages of employing bismuth ferrite Nano catalysts for the environment. An important step toward more sustainable and environmentally friendly biofuel technology is this creative strategy.

Wang et al. (2020) investigated the kinetics of transesterification of waste cooking oil in an electric field, an essential step in the transformation of used cooking oils into biodiesel [67]. The researchers discovered that by increasing the rate of reaction, the electric field enhanced biodiesel synthesis. The biodiesel's output and quality were influenced by a number of variables, including temperature, electric field intensity, and reaction time. They also developed a kinetic model to help explain the transesterification process in an electric field. Insights into reaction mechanics and recommendations for industrial-scale applications were provided by this model. The study highlights the potential of used cooking oil as a sustainable feedstock for the production of biodiesel and advances knowledge of the role that electric fields play in transesterification in keeping with the growing emphasis on the use of waste materials for energy production.

Naeem et al. (2021) studied uses a novel heterogeneous solid base catalyst to investigate the sustainable generation of biodiesel from used cooking oil [68]. To optimize reaction

parameters, such as temperature, catalyst concentration, and reaction duration, the authors carried out a thorough kinetic study. In order to identify the ideal circumstances for the transesterification process, they also looked into a number of operational characteristics. A response surface approach was used in the optimization study to determine the ideal catalytic performance. The suggested catalyst performed better than conventional homogeneous catalysts in terms of activity due to advantages like reusability and a lower impact on the environment. The authors emphasized the significance of using waste oils as a feedstock for the production of alternative fuels and waste management. By lowering reliance on traditional petroleum-based fuels and offering a feasible substitute for sustainable energy production, this effort significantly advanced the manufacture of biodiesel. The findings are in line with those of previous research, which sought to incorporate novel catalytic methods into the process of making biodiesel.

Sharma, Kodgire, and Kachhwaha (2020) investigated the use of ultrasound-assisted transesterification to produce biodiesel from cotton seed leftover cooking oil [69]. Using calcium oxide (CaO) and potassium hydroxide (KOH) as catalysts, the researchers concentrated on process optimization. According to the findings, ultrasound-assisted methods significantly enhanced the transesterification reaction, accelerating the oil-to-biodiesel conversion. The researchers adjusted catalyst concentration, reaction temperature, and time to improve yield. The improved conversion rates and quicker reaction times of the ultrasound-assisted method made the method for producing biodiesel more efficient. The study also emphasized the financial and environmental advantages of employing waste oils as feedstocks for the manufacturing of biodiesel, which increases productivity and lowers the need for high-energy inputs. This study highlights the potential of ultrasound-assisted catalysis as a sustainable alternative for the synthesis of biodiesel, adding to the expanding body of green energy solutions.

Brito et al. (2020) investigated the use of a transesterification method that includes lithium hydroxide (LiOH) in catalyst combinations to produce ecologically friendly biodiesel from used cooking oil [70]. The study shows how waste cooking oil may be recycled into a sustainable feedstock for biodiesel manufacturing, which will help with waste management and the advancement of renewable energy. The efficiency of this technology in reducing environmental impact was demonstrated by the authors' discovery that employing LiOH in conjunction with other catalysts improved biodiesel production. The study also emphasized the significance of choosing the right catalysts to increase conversion efficiency and reaction rates,

providing an alternative to conventional techniques that frequently call for costly or less ecologically friendly catalysts. The study shows that household waste oils can be a practical and eco-friendly alternative, and it adds to the expanding body of knowledge on sustainable biodiesel manufacturing technology.

Hazrat et al. (2022) investigated the kinetic modelling of the esterification and transesterification procedures for the production of biodiesel from waste oils is investigated in this work [71]. In order to increase both quantity and quality, it emphasizes how crucial it is to optimize reaction parameters, such as temperature, catalyst type, and feedstock content. By calculating the reaction kinetics for both processes using mathematical modelling, the authors advanced our knowledge of the metabolic mechanisms underlying these processes. The choice of catalyst and operational parameters had a considerable impact on both processes, according to the study. Under ideal circumstances, transesterification typically yielded biodiesel of superior grade. In keeping with international initiatives to lessen waste and reliance on virgin oils, the study also emphasized the possibility of waste-based feedstocks in the manufacturing of biodiesel. By increasing efficiency through kinetic modelling, the study establishes the foundation for the manufacture of biodiesel, which will be both economical and ecologically benign.

Aneu, Wijaya, and Syoufian (2022) investigated the catalytic potential of modified porous silica in the conversion of biodiesel was examined in a study that was published in the Journal of Porous Materials [72]. The significance of using used cooking oil as an inexpensive feedstock for environmentally friendly biodiesel manufacturing was emphasized by the researchers. According to the study, the addition of potassium fluoride and sulfuric acid greatly increased the catalytic activity of porous silica, improving the conversion efficiency of waste oil into biodiesel. Combining these changes produced the ideal transesterification process by striking a balance between acidity and basicity. The study showed that this technique preserves the environmentally beneficial qualities of waste materials while increasing biodiesel output. The study also demonstrated the potential for producing renewable energy from porous materials treated with basic and acidic chemicals.

Tchuifon et al. (2020) conducted a study on the transesterification reaction of used cooking oil to make biodiesel, which helped to spark interest in alternate energy sources [73]. As a sustainable raw material for the production of biodiesel, their study investigated the possibility of making use of used cooking oil, a feedstock that is inexpensive and readily available. The study emphasized the need to optimize the transesterification process, which creates biodiesel

and glycerol by combining used cooking oil with methanol in the presence of a catalyst. According to Tchuifon et al., the molar ratio of oil to methanol, reaction time, temperature, and catalyst concentration all have an impact on biodiesel production efficiency. The authors provided a viable solution to the twin issues of waste management and sustainable energy production by demonstrating that spent cooking oil can be effectively converted into high-yield biodiesel. In addition, their research suggested that the conversion of used cooking oil into biodiesel could lessen the demand for conventional fossil fuels and the negative effects on the environment associated with its disposal. Their findings promoted sustainable practices, advanced the field of renewable energy, and confirmed previous research demonstrating waste oils are a good feedstock alternative for biodiesel. In particular in regions where residual cooking oil is prevalent, this research will have a significant impact on the development of low-cost, environmentally friendly energy options.

Chen et al. (2021) investigated bibliometric analysis was carried out to investigate the viability of producing biodiesel from used cooking oil [74]. The study emphasized the growing interest in using used cooking oil as a feedstock for the production of biodiesel due to its positive effects on the economy and environment. The study recognized a number of scientific advancements, including advancements in transesterification processes and catalysts, in addition to highlighting difficulties like high manufacturing costs, technical constraints, issues with feedstock quality, and supply chain issues. The viability of biodiesel synthesis is strongly influenced by the optimization of reaction conditions and efficient waste oil collection and purification methods. Even though biodiesel is a renewable alternative to fossil fuels, it still faces competition from other renewable energy sources and must address emissions throughout its lifespan. The study concluded that additional research and development are required to improve the efficacy and scalability of biodiesel production from used cooking oil.

Singh et al. (2021) examined the process of producing biodiesel from used cooking oil in order to demonstrate its potential as a cleaner feedstock for compression ignition engines of the third generation [75]. The authors emphasize the advantages of using used cooking oil because it is less expensive and has a smaller impact on the environment than conventional fuels. Additionally, they look at the energy content, viscosity, and performance properties of biodiesel in diesel engines. The study found that biodiesel made from cooking oil leftovers can successfully replace conventional diesel fuel by offering comparable engine performance, lower emissions, and improved combustion efficiency. But the authors also emphasized the difficulties in producing biodiesel, including gathering feedstock, purification processes, and

technological limitations. Despite these challenges, the authors concluded that biodiesel made from used cooking oil is a promising renewable energy source that has the potential to meet global demand for alternative fuels while also promoting environmentally friendly energy and sustainability.

Mawlid, Abdelhady, and El-Deab (2023) examined A highly effective K2CO3-supported MgFe2O4 magnetic Nano catalyst for the low-temperature production of biodiesel from used cooking oil has been created [76]. This approach has drawn attention because of its effectiveness in producing sustainable energy. The magnetic Nano catalyst showed exceptional efficiency under mild conditions, according to the study, which employed (RSM) to improve the catalytic process. By examining the reaction's kinetics and thermodynamics, the authors were able to shed light on the energy requirements and reaction mechanisms. The magnesium ferroelectric oxide (MgFe2O4)-based Nano catalyst enhanced the production of biodiesel and provided benefits in terms of recyclability. After every cycle, the catalyst's magnetic properties made separation simple. This study adds to the expanding corpus of research on sustainable substitutes for traditional biodiesel manufacturing. It highlights how crucial it is to improve reaction conditions and the function of effective catalysts in boosting the synthesis of biodiesel from waste materials. Additionally, the study emphasizes the potential of Nano catalysis in waste-to-energy processes, promoting more investigation into industrial applicability and scalability for sustainable energy solutions.

Falowo et al. (2022) developed a green heterogeneous base catalyst for the transesterification of used cooking oil by combining ripe and unripe plantain peels [77]. The study looked at this environmentally friendly alternative to conventional homogeneous catalysts, which frequently require complicated separation procedures and contain hazardous chemicals. The study demonstrated that it is both cost-effective and highly effective to use waste biomass as a catalyst precursor. By combining ripe and unripe plantain peels with strong catalytic activity, waste cooking oil was successfully converted into biodiesel. The findings support the growing trend of environmentally friendly, low-cost biodiesel production methods, which offer a viable option for reducing fossil fuel dependence and minimizing environmental harm. The catalyst's capacity to facilitate efficient transesterification reactions was especially important for large-scale applications, where factors such as cost and impact on the environment are crucial.

Cao et al. (2022) included a new catalyst, MgO@CNT@K2CO3, was investigated for enhancing the production of biodiesel from waste edible oil by using a two-step transesterification process [78]. The combination of potassium carbonate, magnesium oxide,

and carbon nanotubes significantly improved both the catalytic process and the synthesis of biodiesel, according to the findings of the researchers. The researchers also emphasized the significance of controlling reaction parameters like temperature, time, and catalyst concentration in order to improve biodiesel production. The two-step transesterification procedure, which involves acid and alkaline catalysis, effectively converted the high concentration of free fatty acids in waste oils into biodiesel. This study adds to the growing body of research on how to make biodiesel production more efficient and friendlier to the environment, especially by using waste oils as cheap and plentiful feedstock. The study proposes a viable strategy for creating more eco-friendly and efficient catalysts for large-scale biodiesel production processes, which will support the development of renewable energy sources.

Dehghani and Haghighi (2020) examined researchers have investigated the conversion of waste cooking oil into biodiesel using sono-enhanced dispersion of CaO over Zr-doped MCM-41 bifunctional Nano catalysts [79]. They doped MCM-41 with zirconium and added a calcium oxide catalyst to make it more stable and effective during the transesterification process. Better biodiesel standards and increased yields were the outcomes of the optimal silicon to zirconium ratio. The study also demonstrated that Sono chemical approaches can be used to improve catalyst dispersion, which further boosts total catalytic activity. The Sono-enhanced method significantly increased conversion rates over conventional methods when combined with Zr-doping. By highlighting the potential of modified MCM-41 materials in sustainable biodiesel production, this study contributes to the growing body of research on environmentally and economically acceptable renewable energy sources. The findings have particular relevance for expanding the use of discarded cooking oil and developing nano catalyst technology for environmentally friendly chemical applications.

John et al. (2023) investigated the use of biodiesel made from used cooking oil as a substitute fuel source, using FeO nanoparticles to improve its efficiency [80]. The authors discovered that adding FeO nanoparticles increased the biodiesel's durability and performance under a range of operating situations in addition to improving combustion efficiency. This is consistent with earlier research showing how crucial waste-to-energy technologies are to reducing pollution and addressing fuel shortages. The study also demonstrated how metal nanoparticles, such as FeO, can improve the physicochemical characteristics of biodiesel, including lower emissions and higher thermal efficiency. The study adds to the expanding body of research on waste-derived fuels and raises the possibility that biodiesel enhanced with FeO nanoparticles could

be a viable option for waste management, energy sustainability, and sustainable energy production.

Sahani, Roy, and Sharma (2020) investigated a novel waste management strategy by producing biodiesel from used cooking oil as a raw material [81]. The researchers used Sr-Ti mixed metal oxide as a solid catalyst to improve the transesterification process, which resulted in a significant increase in the production of biodiesel. To ascertain the ideal parameters for the reaction, such as temperature, catalyst concentration, and reaction duration, they carried out optimization studies. The process's environmental impact, cost-effectiveness, energy efficiency, and sustainability were assessed using e-metrics. High-quality biodiesel was produced as a result of the Sr-Ti catalyst's enhanced catalytic activity over conventional catalysts. Through the use of novel catalytic materials and optimization techniques, the research seeks to increase the sustainability and efficiency of biodiesel synthesis. The results can be used in both industrial and scholarly applications.

Aghel et al. (2022) provided using a nano GO@MgO catalyst in a microreactor, the study explores the production of biodiesel from high-acidity waste cooking oil [82]. The researchers set out to tackle the difficulties associated with processing used cooking oil, which frequently has high acidity levels and can obstruct traditional catalytic processes. They employed GO@MgO, a new nano-composite catalyst that enhanced reaction speeds and raised biodiesel yields. Triglycerides converted to biodiesel at a faster rate thanks to the microreactor system's enhanced heat and mass transfer, which also reduced the waste oil's acidity. The potential of waste-to-energy methods in renewable energy systems is supported by this finding. The results provide light on the role that enhanced catalytic materials and microreactor systems play in optimizing the production of biodiesel, which has important ramifications for the widespread adoption of renewable energy technology.

Al-Saadi, Mathan, and He (2020) investigated SrO–ZnO/Al2O3 is a bifunctional catalyst that has been developed by researchers in order to produce biodiesel from highly acidic waste cooking oil [83]. This novel strategy addresses the issue of waste oils with high concentrations of free fatty acids, which typically necessitates two steps. By combining the properties of an acid catalyst for esterification and a base catalyst for transesterification, the catalyst improves efficiency and overall yield of biodiesel. Temperature and catalyst loading were altered to boost biodiesel yield after careful analysis of the catalyst's performance. The study focused on using used cooking oil as a feedstock to increase reaction efficiency, reduce environmental impact, and offer a sustainable solution for managing waste. The researchers discovered that this

technology could produce biodiesel from a cheap and renewable source, encouraging the production of cleaner energy, and that it was more cost-effective than conventional methods. Their research assisted in the transition to renewable energy sources and promoted sustainable biofuel technology by providing advice on the design of effective catalytic systems for the production of biodiesel.

Niju et al. (2020) examined the use of modified Malleus Malleus shells as a catalyst for the production of biodiesel from used cooking oil in an effort to meet the growing demand for renewable energy and sustainable waste management [84]. The statistical method known as the Box-Behnken design was used to identify the primary variables that had an effect on the amount of biodiesel produced during the transesterification process. Because of their large surface area and strong catalytic capabilities, the researchers discovered that modified Malleus Malleus shells were a good alternative to conventional chemical catalysts. The optimal transesterification process parameters were found using the Box-Behnken design, which increased biodiesel production while reducing environmental effect. The study also showed how statistical optimization approaches can be used to increase biofuel production's yield and process efficiency. By providing a low-cost and environmentally friendly method of producing biodiesel, showcasing the advantages of waste biomass in green energy solutions, and promoting innovation in sustainable energy technologies, this study promotes renewable energy.

Bhonsle et al. (2022) studied in an effort to provide a more sustainable option to conventional biodiesel production processes; researchers have created a special solvent for the room temperature transesterification of waste cooking oil [85]. RSM was used to optimize the process, which usually calls for high temperatures and a large amount of energy input. The procedure became more economically feasible with the new solvent since it not only improved the reaction efficiency under typical circumstances but also increased the amount of biodiesel produced. Because it decreased the carbon footprint connected with the manufacture of biodiesel, the process was also more environmentally friendly and energy-efficient. A more thorough examination of the interactions between different components was made possible by the use of RSM, which improved knowledge of the factors that contribute to the maximum transesterification efficiency. According to the research, leftover cooking oil and other waste oils can be turned into a useful resource for the manufacturing of biodiesel, supporting sustainable energy sources and a circular economy.

Patchimpet et al. (2021) studied using waste cooking oil as the feedstock, Patchimpet's study investigated the application of ultrasonic augmentation in lipase-catalyzed transesterification for the generation of biodiesel [86]. The researchers sought to address issues with current techniques, especially when utilizing waste oils such as leftover cooking oil. The lipase enzyme's catalytic activity was enhanced by the use of ultrasonic waves, which improved the production of biodiesel and raised reaction efficiency. The study sought to maximize temperature, reaction time, and ultrasonic intensity as well as other experimental parameters. According to the results, the ultrasonic-assisted technique outperformed traditional chemical-catalyzed procedures in terms of biodiesel production and reaction speed. The procedure also produced fewer byproducts, making it an environmentally beneficial option. By turning waste into a useful renewable resource, the use of used cooking oil provides an effective waste-to-energy solution and aligns with sustainable energy policies. The study demonstrates the potential of ultrasound-assisted enzymatic transesterification in the synthesis of biodiesel, which advances the creation of more sustainable and ecologically friendly renewable energy solutions.

Mawlid, Abdelhady, and El-Deab (2022) utilized new SrO/MgFe2O4 magnetic nanocatalyst has been created by researchers to increase the efficiency of biodiesel production at low temperatures [87]. The researchers focused on improving process parameters like temperature, catalyst concentration, and reaction time in order to produce high biodiesel yields while maintaining sustainability and cost-effectiveness. The SrO/MgFe2O4 catalyst effectively facilitated the production of biodiesel by reducing activation energy and increasing reaction rate. The catalyst is a viable option for large-scale biodiesel synthesis because of its capacity to function in benign reaction conditions. The catalyst's magnetic qualities also facilitate separation and repurposing, which makes the process eco-friendly. The results add to the increasing amount of study on improving the procedures used to make biodiesel, especially when it comes to using used cooking oil as a feedstock. The study emphasizes how Nano catalysts might improve the biodiesel production processes' economic viability and environmental sustainability, which is essential for the advancement of renewable energy technologies in the future.

Rocha-Meneses et al. (2023) reviewed the most recent advancements in the process of turning WCO into biodiesel have been thoroughly studied by the writers, who have concentrated on reactor systems, catalytic materials, and optimization strategies [88]. They emphasized WCO's affordability and sustainability as a feedstock for the manufacturing of biodiesel. The review

looked at the benefits of different reactor designs in terms of yield, energy use, and operational stability, including batch, continuous, and membrane reactors. The study also looked at how both homogeneous and heterogeneous catalysts might improve the quality of biodiesel and the transesterification reaction's efficiency. To enhance the production process, the scientists looked into optimization strategies like temperature, pressure, reaction time, and catalyst concentration. Issues like catalyst deactivation, reactor scalability, and environmental problems still exist despite advancements in reactor design, catalyst innovation, and process optimization. The authors urge more study to increase the sustainability and feasibility of producing biodiesel using WCO.

Gómez-Trejo-López et al. (2022) investigated the transesterification of used cooking oil to create biodiesel using a sulfonated polyphenylsulfone catalytic membrane has been investigated [89]. An analysis of the membrane's effectiveness revealed that, in comparison to traditional techniques, it greatly increased the generation of biodiesel. The membrane is a great option for producing biodiesel in a sustainable manner because of its durability, reusability, and catalytic qualities. The significance of using used cooking oil as a feedstock and the possibility of this membrane-based technology as an economical and ecologically friendly substitute for current biodiesel production techniques were also emphasized in the study. This study adds to the expanding body of research on biodiesel production process optimization and focuses on developing novel materials that improve the sustainability and efficiency of renewable energy sources.

Weldeslase et al. (2023) utilized a study sought to maximize the production of biodiesel from used cooking oil by employing a zinc-doped calcium oxide catalyst based on lime [90]. Waste cooking oil is a readily available, low-cost feedstock that has attracted attention for its potential to reduce environmental impact. The authors used RSM to optimize critical reaction parameters like reaction temperature, reaction duration, and catalyst concentration. The results demonstrated a significant increase in reaction efficiency and biodiesel output when compared to conventional methods. This study made a significant addition to the body of knowledge regarding the synthesis of waste oil biodiesel and emphasized the significance of response surface techniques in the process of optimizing intricate chemical processes. Both the transition to renewable energy sources and the development of green energy solutions, which are essential components of international sustainability projects, are bolstered by the findings. The research adds to the growing body of knowledge about making biodiesel from used oil.

Karmakar and Halder (2021) aimed to improve the biodiesel production process by overcoming the obstacles posed by current technologies, which frequently require lengthy reaction times and high energy consumption [91]. A novel strategy, the superheated addition of 2-propanol and methanol, was investigated in order to speed up the process of converting used cooking oil into biodiesel. The researchers found that the reaction rate significantly accelerated when 2-propanol and methanol were given together in superheated conditions. This led to higher biodiesel yields and a more rapid transesterification process. This innovation not only increased the efficiency of biodiesel production but also provided an environmentally sustainable alternative by using waste cooking oil, a readily available and reasonably priced feedstock. The findings demonstrate that, in comparison to conventional approaches to the production of biodiesel, this strategy has the potential to cut down on both operational costs and energy consumption. The research contributed to the growing amount of work focused on improving the procedures used in the production of biofuels. It highlighted the importance of different reaction conditions and solvents in the advancement of renewable energy technology.

Roy et al. (2020) examined a new and environmentally responsible method of producing biodiesel by using used cooking oil as fuel [92]. By focusing on the utilization of a single-phase BaSnO3 solid base catalyst, they significantly increased the efficacy of the transesterification process. The authors investigated the catalytic mechanism as well as the kinetics in order to provide a comprehensive comprehension of the manner in which BaSnO3 facilitates the transformation of used cooking oil into biodiesel. Significant information about the catalyst's activity throughout the reaction was obtained from an electrochemical (E-study) analysis that was conducted as part of the investigation. The catalyst's exceptional stability and catalytic activity made it a potential alternative to conventional liquid base catalysts, as their research demonstrated. Roy et al. significantly advanced the development of sustainable biodiesel production methods by using used cooking oil as a feedstock. This option provided a more ecologically friendly method that tackles waste management and the production of renewable energy. This study, which was published in the Journal of Cleaner Production, demonstrated how solid base catalysts can increase biodiesel production while also offering a useful way to lessen the environmental impact of biodiesel.

Topare, Patil, and Khedkar (2020) investigated the study's main focus is on turning wasted cooking oil into biodiesel, a renewable feedstock that can replace traditional fossil fuels [93]. Transesterification was the main method employed by the researchers to turn leftover cooking oil into biodiesel, indicating that it has the potential to reduce the environmental problems

related to the disposal of used oil. The study also looked at how well biodiesel blends performed in terms of emissions when compared to regular diesel. It found that the blends produced fewer dangerous pollutants, such as nitrogen oxides, carbon monoxide, and particulate matter, suggesting that they may be used as ecologically acceptable alternatives. In order to enhance the quality of biodiesel, the authors also emphasized the significance of optimizing catalyst types and reaction conditions. Our understanding of how biodiesel, which is made from used oil, can be used in place of petroleum-based fuels as an environmentally friendly and renewable energy source grows as a result of the findings. This promotes long-term energy production sustainability.

Haq et al. (2021) studied in order to demonstrate remarkable photocatalytic performance in the photodegradation of organic compounds and the transesterification of waste edible oil into biodiesel, researchers have created surfactant-assisted SiO2-Cu@Fe2O3 nanofibers [94]. Using Fe2O3 nanofibers, the researchers altered the surface of copper (Cu) in a SiO2 matrix. The nanofibers were found to be very successful at breaking down dangerous organic pollutants when exposed to light, suggesting that they could be used for environmental clean-up. In the transesterification process, the nanofibers also showed encouraging catalytic activity, allowing waste oils to be converted into biodiesel and assisting in the production of sustainable energy. The nanofibers' durability and surface characteristics were much improved by the addition of surfactants, which also improved their catalytic activity. This study offers a fresh approach to sustainable solutions in pollution reduction and the generation of renewable energy by thoroughly examining the dual functional applications of these nanomaterials in the environmental and energy sectors.

El-sherif et al. (2023) utilized to turn used cooking oil into biodiesel, scientists have created a green CaO-based eggshells/Ag heterogeneous Nano catalyst [95]. The novel catalyst is a more environmentally friendly option than traditional techniques since it uses eggshells as a cheap and renewable source of calcium oxide. It is a more sustainable option than conventional techniques because of its stability, reusability, and catalytic activity. The study also emphasized the advantages of generating biodiesel, a cleaner and sustainable energy source, and recycling used oil. The technique became more economically feasible as a result of the eggshells/Ag Nano catalyst's considerable improvement in reaction yield. This method is a viable substitute for lowering the environmental effects of waste oil disposal and fossil fuel usage since it adds to the expanding corpus of research in green catalysis, waste-to-energy conversion, and sustainable fuel generation.

Elias et al. (2020) conducted using leftover vegetable oil, the study sought to create a bifunctional heterogeneous catalyst for the synthesis of biodiesel [96]. Enhancing the catalyst's performance in transesterification and esterification reactions—which are essential for turning waste oils into biodiesel was the main goal of the study. A combination of materials was used to create the bifunctional catalyst, which was discovered to increase the output of biodiesel by accelerating the process at moderate circumstances. The catalyst was more economical and ecologically beneficial than traditional homogeneous catalysts since it was extremely active and recyclable. The study also emphasized how crucial waste vegetable oil is to lowering environmental problems and promoting the production of renewable energy. The study demonstrated how bifunctional heterogeneous catalysts could be used as an environmentally and economically advantageous biodiesel production option. For the catalyst to be used practically in large-scale biodiesel synthesis, its stability across several cycles was essential, greatly advancing the field of biofuel production.

Helmi and Hemmati (2021) looked into using the magnetically solid base catalyst NaOH/Chitosan-Fe3O4 to produce biodiesel from used cooking oil [97]. The catalyst is made up of iron oxide (Fe3O4), chitosan, and NaOH. The researchers concentrated on increasing the catalyst's potential and improving the reaction conditions. In order to reduce environmental waste, the study focused on using used cooking oil as a sustainable feedstock. Temperature, catalyst concentration, and reaction time were the primary determinants of biodiesel generation. The thermodynamic analysis suggested appropriate conditions for the reaction, while the kinetic studies demonstrated that the reaction followed a certain rate law. The results shed light on process viability and energy requirements. By improving process sustainability and cost-efficiency, the application of magnetically separated catalysts for biodiesel synthesis could significantly contribute to the production of renewable energy.

Akream et al. (2024) investigated an activated carbon-based high-yield ZnO-Ce bifunctional catalyst for the production of biodiesel from used cooking oil [98]. The catalyst, which is a mixture of zinc oxide (ZnO) and cerium oxide (CeO2), improves the processes of esterification and transesterification that are involved in the production of biodiesel. Activated carbon can be utilized as a support material to boost catalytic efficiency due to its large surface area and porosity. The catalyst's effectiveness is due to the synergy of the components. In addition, the study provides advice on how to alter reaction conditions to achieve the highest possible conversion rate. This dual-purpose catalyst offers a viable alternative to conventional methods that frequently rely on costly or less friendly catalysts in the production of sustainable biodiesel,

as demonstrated by the findings. The work contributes to ongoing research on improving the efficiency and long-term viability of biodiesel synthesis from used cooking oil by highlighting the significance of affordable and effective catalytic systems in fostering a transition to green energy.

Velmurugan and Warrier (2022) conducted with the intention of converting used cooking oil into biodiesel by means of a mesoporous MgO-SnO2 nanocomposite [99]. Their study brought to light the growing interest in the production of biodiesel as an environmentally friendly alternative to fossil fuels made from used cooking oil. This not only aids in the management of waste but also promotes sustainability in the energy sector. The utilization of cooking oil that has been left over is specifically stoking this curiosity. The MgO-SnO2 nanocomposite was used as a catalyst by the authors to improve the transesterification process, which is necessary for the production of biodiesel. By making use of the nanocomposite's mesoporous structure, they were able to accomplish this. The researchers found that the mesoporous nanocomposite had better catalytic properties than conventional catalysts, resulting in increased biodiesel production. By demonstrating that nanocomposites can be used to increase reaction efficiency and reduce the environmental impact of the biodiesel manufacturing process, this work contributed to the advancement of biodiesel production technologies. The significance of advancing research into waste-to-energy technology, reducing reliance on conventional fuels, and developing new, environmentally friendly materials for the production of biofuels was emphasized by these findings.

Bousba et al. (2024) investigated the development of a novel NaOH/CoFe2O4 magnetic nano-catalyst for the production of biodiesel from used cooking oil [100]. The research aims to make biodiesel production less harmful to the environment and more effective. Because of the catalyst's magnetic properties, separation and reuse are made easier, which lowers costs and benefits the environment. The utilization of waste oils, including recycled cooking oil, as a substitute source of renewable energy is also highlighted in the paper. The yield and reaction capacity rose as a result of additional process improvements. The study offers insightful information on the potential of nano-catalysts in the manufacture of biodiesel and the improvement of sustainable and efficient biofuel production techniques. The work advances our knowledge of the potential of nano-catalysts in the synthesis of biodiesel.

Ulukardesler (2023) investigated the use of a variety of catalysts to convert leftover cooking oil into biodiesel [101]. According to the study's findings, there has been an increase in interest in renewable energy sources as a result of the need to address environmental issues, particularly

the reliance on fossil fuels. Biodiesel, a more environmentally friendly alternative to conventional diesel fuel made from petroleum, has been identified as an important feedstock for its production. This study examined the efficacy of various catalyst types, including homogeneous, heterogeneous, and enzymatic catalysts, in order to improve the biodiesel manufacturing process's productivity and yield. The findings demonstrated that a cost-effective and environmentally friendly method for producing biodiesel was provided by heterogeneous catalysts, particularly those made from natural materials. Additionally, the study emphasized the economic and environmental advantages of using used cooking oil as a feedstock. In addition to reducing the environmental impact of garbage disposal, this promotes the use of alternative energy sources. This study provided fresh perspectives on how to maximize the production of biodiesel and emphasized the need for sustainable energy practices.

Tarigan et al. (2023) investigated in order to maximize the production of biodiesel, scientists have devised a method that intensifies the amidation of (FFAs) from used cooking oil [102]. The high levels of FFAs in waste oils, which impair the efficiency of conventional biodiesel production methods, are addressed by this strategy. The amidation reaction between FFAs and amines was enhanced by homogenization, which raised the reaction rate and produced more biodiesel. The study discovered that by employing waste oils, this intensified procedure not only enhanced the biodiesel production process but also resulted in a more environmentally friendly strategy. According to the study, using a homogenizer to synthesize biodiesel on a big scale from inexpensive, renewable feed materials may be a viable strategy. This study adds to the expanding corpus of research on biodiesel production technology, which aims to minimize the costs and environmental impact of manufacturing biodiesel while reducing reliance on edible oils. By making use of waste materials, which are frequently underutilized in the generation of energy, the study adds to the broader initiatives to increase the sustainability of biofuel.

Tamjidi et al. (2022) employed a CoFe2O4@GO Nano catalyst to assess the viability of using ultrasonic to produce biodiesel from leftover edible oil [103]. They optimized the effectiveness of a two-stage transesterification process by applying (RSM). The scientists showed that the transesterification reaction was significantly enhanced by using ultrasound as a tool, which increased the amount of biodiesel produced. Apart from improving the process's efficiency, using CoFe2O4@GO as a Nano catalyst not only made recycling the material simpler but also made it a desirable choice for producing ecologically friendly biodiesel. The findings of their investigation showed that the Nano catalyst and ultrasonic have complementary effects, which

decreased the reaction's duration and increased the process's overall efficiency. RSM was used in the optimization process to fine-tune the reaction parameters and maximize the biodiesel yield while achieving high conversion rates. The research made a substantial contribution to the literature by offering practical insights into the use of waste edible oil for the production of biodiesel, while simultaneously addressing environmental issues and the possibility of economically repurposing waste oils. Furthermore, the use of a reusable Nano catalyst provided an environmentally benign and economically viable approach, which was consistent with the growing demand for biofuel production methods that are environmentally conscious.

Azzena et al. (2023) examined in order to show the possibility of turning this waste material into useful goods, the study investigates the recovery, purification, analysis, and chemical modification of used cooking oil [104]. The waste oil was purified and modified by the authors using a variety of methods, including chemical treatments, to make it more suitable for a range of applications. In order to make sure the oil's quality satisfied the necessary standards for additional processing, the study also looked at its chemical characteristics. This study made a substantial contribution to our knowledge of the possible uses of used cooking oil as a raw material for the creation of biofuel and other chemicals. The study emphasized the financial and environmental advantages of recycling spent oil, encouraging environmentally friendly behaviors, and cutting waste. The feasibility of these processes was examined further on a wider scale by Azzena et al. who showed that waste oil can be effectively treated and converted to create higher-value materials. Their results provide a feasible way to lessen the environmental issues related to discarded cooking oils and support the ongoing waste valorization efforts.

Helmi et al. (2022) investigated the electrolysis of used cooking oil into biodiesel using clinoptilolite and phosphomolybdic acid (PMA), a green catalyst [105]. By offering a sustainable alternative to conventional methods, the green catalyst reduces the impact on the environment. The process was optimized using the (RSM), which identified the ideal circumstances for the manufacture of biodiesel. By serving as a renewable energy source and addressing issues associated with trash disposal, cooking oil waste contributes to the circular economy. PMA/clinoptilolite's excellent catalytic activity and stability during the electrolysis process suggest that it could be utilized as a catalyst for the production of biodiesel. RSM's ideal circumstances improved the economic feasibility and efficiency of the biodiesel production process. Waste materials and green catalysts are increasingly being used in the

bioenergy industry, which is advancing research into cleaner and more efficient biodiesel production methods.

Wong, Tiong, and Chin (2023) conducted by pre-treating used cooking oil using a combination of acid esterification and activated carbon adsorption, a study sought to enhance the synthesis of biodiesel [106]. The researchers discovered that waste cooking oil containing high levels of (FFA) decreases the efficiency of traditional transesterification processes. They employed a two-step transesterification process, first lowering FFA levels with acid esterification and then turning triglycerides into biodiesel with alkaline transesterification. By eliminating contaminants like moisture and FFA, the combination of acid esterification with activated carbon adsorption enhanced the output and quality of biodiesel. This pre-treatment procedure greatly increases the efficiency of biodiesel synthesis, making it a viable strategy for large-scale biodiesel production. The study also showed how to use leftover cooking oil sustainably, which lowers pollution in the environment. This is especially crucial when it comes to encouraging alternative energy sources and lowering dependency on traditional fossil fuels.

Bow and Moulita (2020) studied According to the study, the quality of biodiesel produced through induction heating from used cooking oil is significantly influenced by temperature [107]. The ester conversion rate is accelerated by elevated temperatures, which is necessary for the production of biodiesel to be effective. Known for its effectiveness and energy efficiency, induction heating is used to maintain a constant temperature during the transesterification process. The study highlights how crucial it is to maintain exact temperature control in order to guarantee the viscosity, acidity, and purity of biodiesel. It advances understanding of sustainability and the production of biodiesel from discarded oils by making use of waste materials. In line with the increased interest in renewable energy sources and environmentally friendly substitutes for traditional fossil fuels, the study emphasizes the significance of optimizing the heating process to enhance the quality and production of biodiesel.

Roy, Sahani, and Sharma (2020) investigated the kinetics, thermodynamics, and environmental aspects of the biodiesel production process were examined in a study that concentrated on waste cooking oil and castor oil [108]. The researchers examined reaction kinetics and the effects of various factors on the synthesis of biodiesel using a potassium-modified ceria oxide catalyst. The study also looked at how energy and enthalpy changed during the synthesis of biodiesel, which shed light on how successful the process was. The study also assessed the effects on the environment of using castor oil and leftover cooking oil

as sustainable feedstocks for the production of biodiesel. An analysis of the catalyst's function revealed that it increases reaction efficiency, which makes the process more environmentally and economically viable. By showing the potential for waste reduction and more efficient use of renewable resources, the findings aid in the development of cleaner production technologies and enhanced sustainability of biodiesel production processes.

Saad, Siyo, and Alrakkad (2023) investigated the use of Cat, a natural zeolite-based heterogeneous catalyst. TS-7, in the production of biodiesel from WCO and its characterization [109]. The study went into great detail about the production process while also focusing on the structural characteristics and catalytic performance of the catalyst. The authors used Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and XRD to thoroughly characterize the catalyst's physicochemical properties. Their investigation reveals that, Cat. The catalytic activity of TS-7 was high, and it produced a significant amount of biodiesel. Additionally, the study emphasized the long-term viability of using natural zeolite as a catalyst and cooking oil residue as a feedstock, both of which contribute to the environmentally friendly production of biodiesel. By offering a practical and cost-effective alternative to the production of biodiesel, the authors concluded that their suggested strategy addressed both the management of waste and the production of renewable energy.

Khan et al. (2024) investigated the use of a brand-new transition metal-loaded hydrochar catalyst made from rice husk, a waste biomass, to produce biodiesel from WCO [110]. With the goal of increasing biodiesel yield and process efficiency, the study concentrated on the catalytic performance of hydrochar impregnated with transition metals. FTIR spectroscopy, BET surface area analysis, and thermogravimetric analysis (TGA) were some of the analytical techniques used to characterize the catalyst's structure and functionality. The results demonstrated that the transition metal-loaded hydrochar catalyst significantly improved the transesterification process in comparison to conventional catalysts, resulting in higher biodiesel yields. The study also emphasized the possibility of producing biodiesel on a large scale by highlighting the advantages of using hydrochar made from rice husks in terms of both financial and environmental aspects. The authors claim that these catalysts may be a eco-friendlier alternative to conventional homogeneous catalysts, reducing waste production and improving the overall sustainability of biodiesel production.

Amenaghawon, et.al., (2022) conducted an optimization study for the production of biodiesel from WCO using a functionalized bio-based heterogeneous catalyst [111]. The primary focus of the study was on the development of the bio-catalyst and its capacity to maximize reaction

parameters like temperature, catalyst loading, and the ratio of methanol to oil. (RSM) was used to determine the ideal conditions for the highest possible biodiesel yield. The outcomes showed that the functionalized bio-catalyst was a good substitute for traditional catalysts due to its great stability and reusability. Bio-based heterogeneous catalysts' potential to maintain cost-effectiveness while reducing the environmental impact of biodiesel production was also highlighted in the study. The authors concluded that their improved strategy might encourage the biofuel industry to use green catalysts and renewable feedstocks, thereby improving the sustainability and efficiency of biodiesel production.

Al-Hamamre et al. (2023) examined the use of a heterogeneous catalyst made of potassium nitrate (KNO_3) supported on oil shale ash to produce biodiesel from WCO [112]. The goal of the project was to create a biodiesel synthesis catalyst that was effective, economical, and ecologically friendly. Using methods including Fourier transform infrared spectroscopy (FTIR), (SEM), and (XRD), the authors thoroughly characterized the catalyst in order to assess its physicochemical characteristics. According to the results of tests that were carried out on the catalytic activity under a variety of different reaction conditions, the KNO3/oil shale ash catalyst significantly improved the transesterification process, which led to a high production of biodiesel. The study also highlighted the catalyst's potential for large-scale biodiesel synthesis by demonstrating its stability and reusability over multiple reaction cycles. The authors concluded that using oil shale ash, a by-product of the industrial process, as a catalyst could encourage the production of greener energy and raise the value of trash.

Ali et al. (2023) investigated the kinetics of catalyst deactivation and artificial neural network (ANN) modelling in the catalytic generation of biodiesel from WCO in a two-phase oscillatory baffled reactor [113]. The study looked into how temperature, catalyst loading, and residence time affected the amount of biodiesel produced. In order to comprehend the catalyst's deactivation behaviour over extended use and gain insight into its lifetime and efficiency, the authors used kinetic modelling. To further increase the efficiency of biodiesel production, an ANN-based predictive model was created to optimize the process parameters. The findings showed that, in comparison to traditional reactors, the oscillatory baffled reactor greatly improved mass transfer and reaction kinetics, resulting in higher biodiesel yields. The study also highlighted how crucial ANN modelling is for forecasting and maximizing the output of biodiesel, lowering experimental expenses, and enhancing process control. The scientists concluded that combining machine learning methods with kinetic studies could improve the scalability and dependability of biodiesel manufacturing technology.

Grosmann et al. (2022) presented a novel two-step method for producing biodiesel that involves alkali-catalyzed reactive distillation after hydrated metal salt pre-treatment [114]. By optimizing the pre-treatment step, which eliminated (FFA) from WCO prior to transesterification, the study sought to increase the quantity and quality of biodiesel. The pre-treatment procedure dramatically decreased FFA levels, limiting soap formation during the subsequent alkali-catalyzed reaction, according to the authors' testing of many hydrated metal salts. The production process was streamlined by using reactive distillation to improve biodiesel separation and purification. The outcomes showed that the reactive distillation and pre-treatment method together increased conversion rates, decreased catalyst usage, and enhanced the purity of the biodiesel. The study also demonstrated the process's energy efficiency, which makes it a good substitute for traditional batch transesterification techniques. The authors concluded that the manufacture of biodiesel from WCO might be made more environmentally and economically sustainable by incorporating enhanced pre-treatment and increased processing procedures.

El-Khair, El Naga, and Morshedy (2024) investigated the use of a $KOH/ZnAlO_4$ nanocatalyst made from leftover aluminum foil to produce biodiesel from WCO quickly and at low temperatures [115]. In order to maximize the output of biodiesel at mild reaction conditions, the study concentrated on both the kinetic and thermodynamic elements of the transesterification reaction. In order to assess the Nano catalyst's structural and functional characteristics, the authors used methods like Fourier transform infrared spectroscopy (FTIR), (SEM), and (XRD). According to their research, the $KOH/ZnAlO_4$ catalyst demonstrated excellent catalytic efficiency, shortening reaction times and improving the conversion of biodiesel at lower temperatures. The process was also endothermic and spontaneous, according to thermodynamic study, which further supports its viability for producing biodiesel on a wide scale. The study highlighted the potential for lowering industrial waste and the cost of producing biodiesel, underscoring the sustainability of employing recycled aluminum foil for catalyst synthesis. The authors concluded that their technique provided a sustainable and energy-efficient means of producing biodiesel, making it a competitive substitute for traditional catalytic methods.

Fangfang, Alagumalai, and Mahian (2021) examined the sustainability of producing biodiesel from WCO using environmental factor analysis and artificial neural network (ANN) modelling [116]. The study's objective was to use ANN-based predictive modelling to optimize reaction parameters while also assessing the process's impact on the environment. The

researchers gathered experimental data on a variety of transesterification parameters, including the type of catalyst, temperature, reaction time, and methanol-to-oil ratio, in order to train the ANN model. The findings demonstrated that ANN could forecast biodiesel yield accurately and effectively, eliminating the need for prolonged experimental testing. Additionally, a life cycle assessment (LCA) was conducted to investigate energy consumption, carbon emissions, and environmental sustainability as a whole. The study confirmed WCO's position in the sustainable energy transition by demonstrating that its production of biodiesel had a substantially smaller carbon footprint than that of fossil fuels. The scientists concluded that combining ANN modelling with environmental assessments could improve biodiesel production's eco-friendliness and efficiency while also increasing its suitability for industrial uses.

Jayaraman et al. (2022) evaluated how well it worked in a (CI) engine using zinc oxide (ZnO) nanoparticles and tungstophosphoric acid (TPA) as a catalyst to produce biodiesel from WCO [117]. The primary goals of the study were to increase the effectiveness of the catalyst and assess the fuel qualities of the produced biodiesel. The authors synthesized and evaluated the ZnO-TPA catalyst using analytical techniques like XRD, SEM, and BET surface area analysis in order to determine its structural and textural characteristics. The findings indicate that the catalyst had exceptional catalytic activity, resulting in the production of a significant quantity of biodiesel with little soap production. Additionally, the thermal efficiency, pollutants, and characteristics of fuel combustion were evaluated through engine performance tests. The results showed that biodiesel made with ZnO-TPA burned more efficiently and produced fewer harmful CO and NOx emissions than conventional diesel fuel. The study demonstrated ZnO-TPA's potential as a robust biodiesel synthesis catalyst and its suitability for use in diesel engines to lessen pollution in the environment. The authors concluded that using biodiesel in CI engines in conjunction with a catalytic method could lead to cleaner and more sustainable energy options.

Sivarethinamohan et al. (2022) examined the possibility of utilizing solar intensification to produce biodiesel from WCO with the intention of lowering energy consumption and increasing sustainability [118]. During the transesterification process, solar energy was used as a heating source, and the biodiesel's engine performance was also looked at. In their comparison of biodiesel production under conventional and sun-assisted heating, the scientists found that applying solar intensification resulted in a considerable decrease in energy input and an increase in biodiesel yield. In addition, the fuel's efficiency, emissions, and combustion

properties were investigated through studies on engine parameter assessment. Solar-intensified biodiesel had higher thermal efficiency and lower levels of pollutants like NOx and CO, according to the findings. The authors concluded that producing biodiesel with solar energy could save energy, reduce reliance on fossil fuels, and produce biofuels in a way that is better for the environment.

Joshi, Bhanderi, and Patel (2023) gave a thorough analysis of WCO's potential as a source of bio-lubricants, highlighting both the financial and environmental advantages [119]. The chemical makeup of WCO and its suitability for esterification and transesterification methods to transform it into bio-lubricants were investigated in this work. The authors talked about different catalysts and reaction conditions that were optimized for the manufacturing of bio-lubricants, emphasizing the contribution of additives to improving the end product's viscosity and oxidative stability. The review also looked at how well bio-lubricants made from WCO performed in industrial and automotive settings, showing that they were compatible with traditional lubricants, biodegradable, and had lower toxicity. The scientists also discussed issues including thermal degradation and oxidation stability, indicating the necessity for more study on antioxidant compounds and process enhancements. The study found that by repurposing waste oils, WCO-based bio-lubricants could be a sustainable substitute for petroleum-based lubricants, lowering pollution levels and promoting the circular economy.

Hamed et al. (2021) investigated the production of biodiesel from WCO using a homogeneous catalyst, with an emphasis on maximizing yield through the optimization of reaction parameters [120]. The authors looked into how the ratio of methanol to oil, reaction temperature, reaction time, and catalyst concentration affected the efficiency of biodiesel conversion. Their findings showed that, under ideal circumstances, a homogeneous catalyst such as potassium hydroxide (KOH) or sodium hydroxide (NaOH) facilitated effective transesterification and produced a high output of biodiesel. But the study also emphasized problems with homogeneous catalysis, such as wastewater production, soap creation, and catalyst separation. The authors proposed improving purifying procedures and investigating catalyst recovery strategies to lessen these problems. The results addressed the need for better post-reaction treatment to increase the purity of biodiesel while also highlighting the benefits of homogeneous catalysts in terms of cost-effectiveness and reaction speed. Although alternate catalysts and environmentally friendly processing methods should be investigated for industrial-scale applications, the study found that homogeneous catalysis was still a feasible method for producing biodiesel, especially in small-scale operations.

Khan, Maseet, and Basir (2020) examined the use of lipase immobilized on genipin cross-linked chitosan beads as a biocatalyst in a green method for the production of biodiesel from WCO [121]. The aim of the study was to improve enzyme stability and reusability while also reducing environmental impact. The immobilized lipase was characterized using (SEM), Fourier transform infrared spectroscopy (FTIR), and thermal gravimetric analysis (TGA) to confirm enhanced enzyme activity and efficient cross-linking. The experimental results showed that the immobilized enzyme was more effective as a catalyzer than free lipase, leading to a larger production of biodiesel and a shorter reaction time. The study also demonstrated the immobilized enzyme's recyclability, showing that it may be utilized repeatedly without seeing a noticeable decrease in activity. According to the results, lipase immobilization on biodegradable supports like chitosan may offer a viable and environmentally responsible substitute for chemical catalysts in the synthesis of biodiesel.

Bahadoran et al. (2022) investigated the production of biodiesel from WCO using a heterogeneous Nano catalyst made of magnetic polyaniline coated with cobalt oxide [122]. The study's objective was to improve catalyst reusability and efficiency while simultaneously reducing undesirable side reactions. The authors synthesized and analyzed the Nano catalyst with XRD, SEM, and Brunauer-Emmett-Teller (BET) surface area analysis in order to evaluate its structural and textural properties. The findings revealed that the catalyst's exceptional magnetic properties made recovery and reuse simple. Under ideal reaction conditions, the Nano catalyst also showed strong catalytic activity, producing a sizable biodiesel yield. The study also looked at how the efficiency of biodiesel conversion was affected by a number of operating factors, like the ratio of methanol to oil, catalyst loading, and reaction temperature. The authors concluded that the magnetic Nano catalyst offered a viable route to the production of environmentally friendly biodiesel by reducing catalyst waste and energy consumption.

Topare, Patil, and Khedkar (2021) investigated, with an emphasis on optimizing operational parameters, how ultrasonic irradiation affected the generation of biodiesel from WCO [123]. By using ultrasonic waves to improve mass transfer and reaction kinetics, the study sought to improve the transesterification process. The authors looked into how the yield of biodiesel was affected by variables like ultrasonic power, catalyst concentration, and reaction time. When compared to traditional techniques, their results showed that ultrasonic irradiation greatly expedited the reaction and decreased the amount of processing time needed. The study also showed that enhanced mixing and cavitation effects from ultrasonic-assisted transesterification resulted in increased biodiesel output and purity. The authors emphasized the benefits of

ultrasonic technology in the manufacturing of biodiesel, such as decreased reaction time, increased process efficiency, and energy savings. According to their findings, combining ultrasonic irradiation with biodiesel synthesis may help produce biofuel more effectively and economically.

Cerón Ferrusca et al. (2023) reviewed both homogeneous and heterogeneous catalytic techniques, offering a thorough understanding of the catalytic processes for the generation of biodiesel from WCO [124]. The study compared the effectiveness, reusability, and environmental impact of several catalysts, including alkaline, acid, enzyme-based, and Nano catalysts. The authors addressed issues with catalyst deactivation and reaction efficiency while highlighting the benefits of heterogeneous catalysts, such as their ease of separation and recyclability. The study also looked at new developments in catalytic materials, such as hybrid materials and nanostructured catalysts, which have the potential to improve biodiesel yield and process sustainability. The review also underlined how crucial it is to maximize biodiesel conversion by optimizing reaction parameters like temperature, reaction time, and methanol-to-oil ratio. The authors concluded that more research into catalyst development and process optimization could enhance the WCO biodiesel production's economic feasibility and environmental sustainability.

Jain et al. (2023) examined the use of sodium hydroxide (NaOH) as a catalyst in the low-temperature transesterification of an algal oil and WCO blend [125]. By utilizing the high lipid content of algal oil and adding a tiny quantity of WCO to promote sustainability, the study sought to increase the yield of biodiesel. To maximize biodiesel conversion, the authors adjusted reaction parameters such as temperature, catalyst concentration, and reaction time. The findings showed that a lower reaction temperature preserved a high biodiesel production while consuming less energy. The study also demonstrated how feedstock composition affects reaction efficiency, with algal oil contributing to a larger amount of fatty acid methyl ester (FAME). The authors concluded that combining algal oil with WCO offered a practical method of producing biodiesel, lowering reliance on virgin oils and improving the biofuel synthesis's economic feasibility.

Oladipo et al. (2024) investigated using a solid base catalyst made from carob pods to produce biodiesel from WCO with microwave assistance [126]. The goal of the study was to reduce energy usage while improving catalyst efficiency and reaction kinetics. In order to verify the catalyst's structural characteristics, the authors synthesized and described it using methods like (SEM) and (XRD). When compared to traditional heating techniques, experimental results

showed that microwave irradiation greatly expedited the transesterification reaction and shortened the reaction time. The biodiesel output was enhanced by the catalyst made from carob pods' excellent catalytic activity, stability, and reusability. The study also looked at how important variables like reaction time, microwave power, and the methanol-to-oil ratio affect how well biodiesel is made. The researchers concluded that microwave-assisted transesterification in conjunction with bio-derived catalysts provided a sustainable and energy-efficient alternative to the synthesis of biodiesel from WCO.

Xia et al. (2022) examined the electrolytic transesterification of WCO by means of a magnetic Co/Fe–Ca catalyst derived from discarded shells [127]. The aim of the study was to develop an electrolytic catalyst that was both economical and beneficial to the environment in order to improve biodiesel production efficiency. In order to evaluate the catalyst's physicochemical characteristics, the scientists used a variety of analytical methods, such as BET surface area analysis, XRD, and SEM. The magnetic catalyst's high catalytic activity and stability, as shown by the experimental results, made recovery and reuse simple. In comparison to traditional transesterification techniques, the electrolytic transesterification process improved reaction kinetics by promoting charge transfer, resulting in a higher biodiesel output. Additionally, the study demonstrated how using waste shells as a catalyst precursor might benefit the environment by promoting resource sustainability and waste valorization.

Abedin et al. (2014) examined the effects of biodiesel blends made from palm and jatropha oils on diesel engine performance, emissions, and heat losses [128]. The study looked at how these inedible oils affected pollutants and engine performance, as well as whether or not they could be used as alternative fuels. The authors conducted experimental tests by combining regular diesel in various proportions with biodiesel made from palm and jatropha. Because of their higher viscosity and lower calorific value, the results showed that biodiesel blends had a slightly lower brake thermal efficiency (BTE) than pure diesel. However, the environmental benefits of burning biodiesel were highlighted by the much lower emissions of particulate matter (PM), hydrocarbons (HC), and (CO). The study also found that burning biodiesel frequently results in higher emissions of (NOx). Additionally, the heat loss research showed that biodiesel mixes resulted in increased exhaust heat losses, which had an impact on engine efficiency overall.

Atabani (2013) has out a thorough analysis of non-edible vegetable oils for the production of biodiesel, paying particular attention to engine performance, fatty acid composition, fuel qualities, emissions characteristics, and oil extraction techniques [129]. Jatropha, karanja,

mahua, and rubber seed oils were among the non-edible oil sources covered in the assessment, which also highlighted their potential as sustainable feedstocks for biodiesel. These oils' high level of (FFA) made pre-treatment procedures like esterification before transesterification necessary, according to the study's analysis of their physicochemical characteristics. Biodiesel made from non-edible oils dramatically reduced CO, HC, and PM emissions while demonstrating efficiency comparable to diesel fuel, according to engine performance studies. But like with other research, the higher oxygen content of biodiesel was linked to higher NOx emissions. In order to increase the commercial viability of non-edible oil-based biodiesel, the evaluation also looked at its economic and environmental sustainability, emphasizing the necessity of effective cultivation and processing methods.

Avhad and Marchetti (2015) examined new developments in catalytic materials for the manufacture of biodiesel, emphasizing enzymatic and heterogeneous catalysts [130]. The study discussed the effectiveness, reusability, and environmental impact of several catalytic systems, including alkaline, acidic, and biocatalysts. The benefits of heterogeneous catalysts, like zeolites and solid metal oxides, which provided better reaction kinetics and made catalyst recovery easier, were highlighted by the authors. The review also emphasized the potential of enzymatic catalysts, especially immobilized lipases, for the production of biodiesel because of their capacity to function in mild reaction conditions and withstand feedstocks with high FFA content. However, sluggish reaction rates, high production costs, and enzyme deactivation were found to be major obstacles. The study also looked at new approaches to catalyst development, such as magnetic and nanocatalysts, which were intended to improve process sustainability and catalytic efficiency.

Azad et al. (2015) examined the potential of biofuels as a substitute fuel for vehicles in Australia, focusing on the adoption of biofuels' effects on the environment, the economy, and energy security [131]. The study examined the production methods, feedstock availability, and compatibility with current fuel infrastructure of a number of biofuels, including biodiesel, bioethanol, and biogas. The authors talked about how government incentives and regulations might encourage the use of biofuels and lessen reliance on fossil fuels. According to their research, biofuels—especially biodiesel—have the potential to drastically cut greenhouse gas emissions and lessen dependency on fuels derived from petroleum. However, issues like the expense of production, competition from other land uses, and the availability of feedstock were found to be major obstacles to the widespread use of biofuel.

Banković-Ilić et al. (2012) reviewed the benefits, difficulties, and viability of using non-food feedstocks for sustainable biodiesel synthesis in a thorough analysis of the process of producing biodiesel from non-edible plant oils [132]. The study looked at a number of non-food oil sources, including rubber seed oil, neem, karanja, and jatropha oil, highlighting their high lipid content and potential for biodiesel synthesis. In order to improve the yield and quality of biodiesel, the authors examined the transesterification procedure, catalyst selection, and optimization techniques. One of the study's main conclusions was that non-edible oils were a good substitute for edible oils, allaying worries about land use competition and food security. However, problems such a high proportion of (FFA), inefficient oil extraction, and a lack of large-scale production have prevented non-edible oil-based biodiesel from being widely used. In order to increase the productivity and sustainability of biodiesel production, the assessment also emphasized new developments in the field, such as waste valorization, process intensification, and catalyst development.

Cataluña and Da Silva (2012) examined how cetane number affected diesel engine emissions and fuel consumption, offering important new information on how biodiesel and diesel blends burned [133]. With an emphasis on particulate matter (PM), unburned hydrocarbons (HC), and specific fuel consumption (SFC), the study investigated the connection between cetane number, engine performance, and pollutant emissions. Higher cetane values were shown to result in better combustion efficiency, shorter ignition delays, and fewer emissions of particulate matter and unburned hydrocarbons. Although cetane-enhanced fuels improved combustion characteristics, the study also found that their effects on overall fuel economy differed based on engine type and operating conditions. In order to improve the efficiency and sustainability of biodiesel as a diesel alternative, the authors underlined the significance of refining fuel formulations and carrying out additional research on the interaction between cetane number, fuel composition, and engine performance.

Chopade et al. (2012) examined how solid heterogeneous catalysts contribute to the generation of biodiesel, with a particular emphasis on the transesterification of triglycerides with methanol [134]. The study emphasized the benefits of utilizing solid catalysts over traditional homogeneous catalysts, including less wastewater formation, easier separation, and reusability. The authors discussed the catalytic efficiency and operational issues of solid catalysts by classifying them into various groups, such as metal oxides, zeolites, and ion-exchange resins. Heterogeneous catalysts have the potential to improve biodiesel yield and quality while lowering production costs and their environmental impact, according to the review. To increase

the commercial viability of solid-catalyst-based biodiesel generation, the study did, however, also highlight the need for additional research on catalyst stability, reaction kinetics, and large-scale industrial applications.

Choudhury et al. (2014) used a heterogeneous base catalyst to study the mechanistic features of sono chemical biodiesel production [135]. The application of ultrasound-assisted transesterification, which greatly improves mass transfer and reaction rates, was the main focus of the investigation. In their thorough examination of cavitation events, the scientists described how ultrasonic waves produce tiny bubbles that improve catalyst contact and reactant dispersion. In comparison to traditional stirring techniques, their testing results showed that ultrasonic irradiation decreased reaction time, enhanced biodiesel yield, and decreased energy consumption. The study did identify certain difficulties, though, including catalyst deactivation and the requirement for ideal ultrasonic frequency and power settings. The scientists concluded that while sono chemical biodiesel synthesis has a lot of potential to increase sustainability and process efficiency, more study is needed before this technique can be scaled up for industrial use.

Dhar and Agarwal (2014) evaluated Karanja biodiesel's performance, emissions, and combustion properties in a transportation engine and contrasted its effectiveness with that of regular diesel [136]. According to their experimental research, the higher viscosity and lower calorific value of Karanja biodiesel resulted in a little poorer brake thermal efficiency (BTE). However, because of its natural oxygen content, which improved combustion, it greatly decreased emissions of (CO), hydrocarbons (HC), and particulate matter (PM). The study also discovered that while biodiesel blends had greater combustion temperatures, their NOx emissions were marginally higher. The authors concluded that although Karanja biodiesel is a good substitute for petroleum diesel, more engine tuning and fuel formulation optimization are needed to reduce NOx emissions and boost fuel economy.

Gangil et al. (2016) utilized the methyl ester of Karanja oil as a substitute fuel to evaluate the emissions and performance of a diesel engine [137]. As part of their investigation, Karanja biodiesel was experimentally tested in various blend ratios with regular diesel. Even though the lower energy content of biodiesel caused a small decrease, the results showed that blends of biodiesel and diesel fuel produced brake thermal efficiencies (BTEs) that were comparable. Despite this, the study found that biodiesel's higher oxygen content significantly reduced hydrocarbon (HC) and CO emissions, helping it burn more efficiently. On the other hand, in line with previous research on biodiesel, it was discovered that the emissions of (NOx) were

marginally higher. The authors concluded that while Karanja biodiesel is a promising alternative fuel with environmental advantages, its efficiency would require further engine calibration and mix ratio improvement.

Giakoumis (2013) investigated statistically the relationship between the degree of unsaturation in the fatty acid composition and the physical and chemical characteristics of biodiesel [138]. In order to identify important patterns in attributes including viscosity, density, oxidation stability, and calorific value, the study examined biodiesel samples made from various feedstocks. The results showed that biodiesel with a higher degree of unsaturation was more likely to degrade because it had higher iodine values and lower oxidation stability. Furthermore, the quality of ignition was impacted by the tendency of highly unsaturated biodiesel to have lower cetane values. In order to maximize the qualities of biodiesel fuel for improved engine performance and storage stability, the study underlined the need of choosing feedstocks with balanced fatty acid compositions.

Gomes et al. (2012) compared the viability and efficiency of heterogeneous alkaline catalysts with traditional homogeneous catalysts to examine the state of biodiesel manufacturing [139]. The review assessed the catalytic activity, reusability, and operational difficulties of a variety of solid catalysts, including zeolites, alkaline earth metal oxides, and mixed metal catalysts. The scientists discovered that heterogeneous catalysts provide a number of benefits, such as simpler separation, less soap production, and less of an adverse effect on the environment. However, variables like feedstock content, reaction temperature, and catalyst structure affect how well they work. The study concluded that although heterogeneous catalysis holds great promise for producing biodiesel on a wide scale, more investigation is needed to improve reaction kinetics, decrease deactivation, and increase catalyst stability.

Hassan & Kalam (2013) gaved a thorough introduction to biofuels as a sustainable energy source, going over their history, benefits, and related difficulties [140]. The study looked at a variety of biofuels, including biodiesel, bioethanol, and biogas, with an emphasis on their potential to reduce emissions of greenhouse gases and reduce reliance on fossil fuels. The authors emphasized several important issues, including engine compatibility, manufacturing costs, land use rivalry, and feedstock supply. The study also covered technological developments in the manufacture of biofuels, such as second- and third-generation biofuels made from lignocellulosic biomass and algae. The study concluded that although biofuels have potential advantages for the environment and energy security, further research is needed to

improve fuel qualities, increase production efficiency, and remove obstacles relating to policy and the economy.

Hwang et al. (2016) examined the performance, combustion, and emission characteristics of using WCO biodiesel in a compression ignition engine [141]. A single-cylinder diesel engine was used to evaluate different biodiesel-diesel mixtures as part of the investigation. According to the findings, WCO biodiesel's thermal efficiency was comparable to that of regular diesel, albeit somewhat lower because of its reduced calorific value. The study also discovered that because biodiesel blends have a higher oxygen content, which improves combustion, they dramatically lower CO and PM emissions. However, as is often the case with biodiesel fuels, NOx emissions were somewhat higher. In order to reduce NOx emissions while preserving the environmental advantages of biodiesel, the authors suggested adjusting engine specifications and investigating exhaust gas recirculation (EGR) devices.

Lalvani et al. (2016) investigated how a piston that causes turbulence and the injection pressure affected the combustion, emission characteristics, and performance of a biodiesel-powered direct injection (DI) diesel engine [142]. In order to evaluate their effects on fuel atomization, combustion efficiency, and emissions, the study examined various injection pressures and piston types. The results showed that increasing the injection pressure made fuel-air mixing better, which made combustion more efficient and cut down on CO and HC emissions. The turbulence-inducing piston design increased swirl motion inside the combustion chamber to further enhance combustion quality. However, higher in-cylinder temperatures led to an increase in NOx emissions, as is the case with most biodiesel research. According to the study's findings, biodiesel-fuelled engines might become more efficient and more feasible for use in commercial settings by improving their piston design and injection pressure.

Islam et al. (2013) has out a thorough investigation into the design of heterogeneous catalysts for the manufacture of biodiesel, emphasizing the enhancement of environmental sustainability, reusability, and catalytic efficiency [143]. The study examined various catalyst materials, emphasizing their function in boosting transesterification processes, such as metal oxides, mixed oxides, and supported catalysts. The authors highlighted the benefits of heterogeneous catalysts, including simpler separation, less wastewater production, and enhanced process sustainability, by contrasting their performance with that of traditional homogeneous catalysts. According to the study's findings, increasing the yield and efficiency

of biodiesel reactions requires adjusting catalyst characteristics such surface area, pore size, and acid/base strength.

Ismail et al. (2014) examined the process of turning castor oil into biodiesel and using it in diesel engines [144]. In addition to analyzing the fuel's viscosity, calorific value, and cetane number, the study described the transesterification procedure used to turn castor oil into biodiesel. Castor oil biodiesel demonstrated comparable braking thermal efficiency to diesel fuel in engine performance testing, but with lower CO and HC emissions. However, NOx emissions were somewhat greater because castor oil biodiesel had a higher viscosity and a higher oxygen concentration. The authors proposed utilizing additives or mixing castor biodiesel with diesel to assist reduce viscosity-related problems and enhance engine performance.

Jindal (2014) has out experimental studies on the application of n-butanol-blended WCO biodiesel in a (CI) engine [145]. The purpose of the study was to evaluate how the addition of n-butanol affected performance, emissions, and combustion parameters. According to the results, n-butanol increased fuel atomization, decreased ignition delay, and improved combustion efficiency when added to WCO biodiesel. Due to improved combustion, the blend also resulted in a notable decrease in CO and PM emissions. However, because oxygenated fuels have a greater combustion temperature, NOx emissions rose. According to the study's findings, n-butanol shows promise as a co-solvent or additive to enhance WCO biodiesel's performance in diesel engines.

Kaur and Ali (2015a) examined the use of calcium oxide impregnated with molybdenum as a solid catalyst in the ethanolysis of jatropha oil to produce biodiesel [146]. Their research looked at the biodiesel yield, reaction kinetics, and catalytic efficacy under a variety of process conditions. According to the findings, the catalyst impregnated with molybdenum showed excellent catalytic activity, stability, and reusability. The study also showed how temperature, the molar ratio of ethanol to oil, and catalyst loading were important factors that affected the production of biodiesel and the efficiency of the reaction.

Kaur and Ali (2015b) investigated using lithium zirconate as a solid catalyst to transesterify and esterify low-quality triglycerides at the same time [147]. The study evaluated how well the catalyst converted triglycerides and free fatty acids into biodiesel in a single step. According to the findings, lithium zirconate efficiently lowered the acid value and promoted a

high yield of biodiesel. The catalyst also shown remarkable reusability and thermal stability, which makes it a viable choice for producing biodiesel from feedstocks high in free fatty acids.

Kumar and Ali (2013) investigated the use of a Zn/CaO heterogeneous catalyst for the transesterification of low-quality triglycerides [148]. Reusability, catalyst activity, and reaction kinetics were the main topics of their investigation. The findings showed that, in mild reaction conditions, the Zn/CaO catalyst produced good biodiesel conversion rates. Additionally, the catalyst showed good reusability over several cycles with negligible activity loss. According to the study's findings, Zn/CaO may be an economical and effective catalyst for producing biodiesel from subpar feedstocks.

Kumar Maurya and Kumar Agarwal (2014) examined the combustion and exhaust properties of the n-butanol-fueled HCCI (Homogeneous Charge Compression Ignition) engine [149]. The study looked at trends in emissions, thermal efficiency, and ignition behavior in a variety of operating conditions. In comparison to traditional diesel fuel, the results showed that n-butanol decreased NOx and particulate matter emissions and enhanced combustion stability. But inefficient combustion at lower loads also resulted in higher carbon monoxide emissions, according to the study. According to the authors, n-butanol-fuelled HCCI engines may operate even better if engine parameters were optimized.

Li et al. (2015) investigated the emission and combustion properties of a diesel engine running on mixtures of diesel, biodiesel, and pentanol [150]. According to their research, pentanol's higher oxygen concentration enhanced combustion efficiency and decreased soot emissions when added to the fuel blend. Additionally, the study found that the addition of pentanol marginally increased NOx emissions and ignition delay. In contrast to traditional diesel, the total emission profile was discovered to be more ecologically benign. The authors concluded that pentanol would be a useful oxygenated ingredient for enhancing the performance of biodiesel blends.

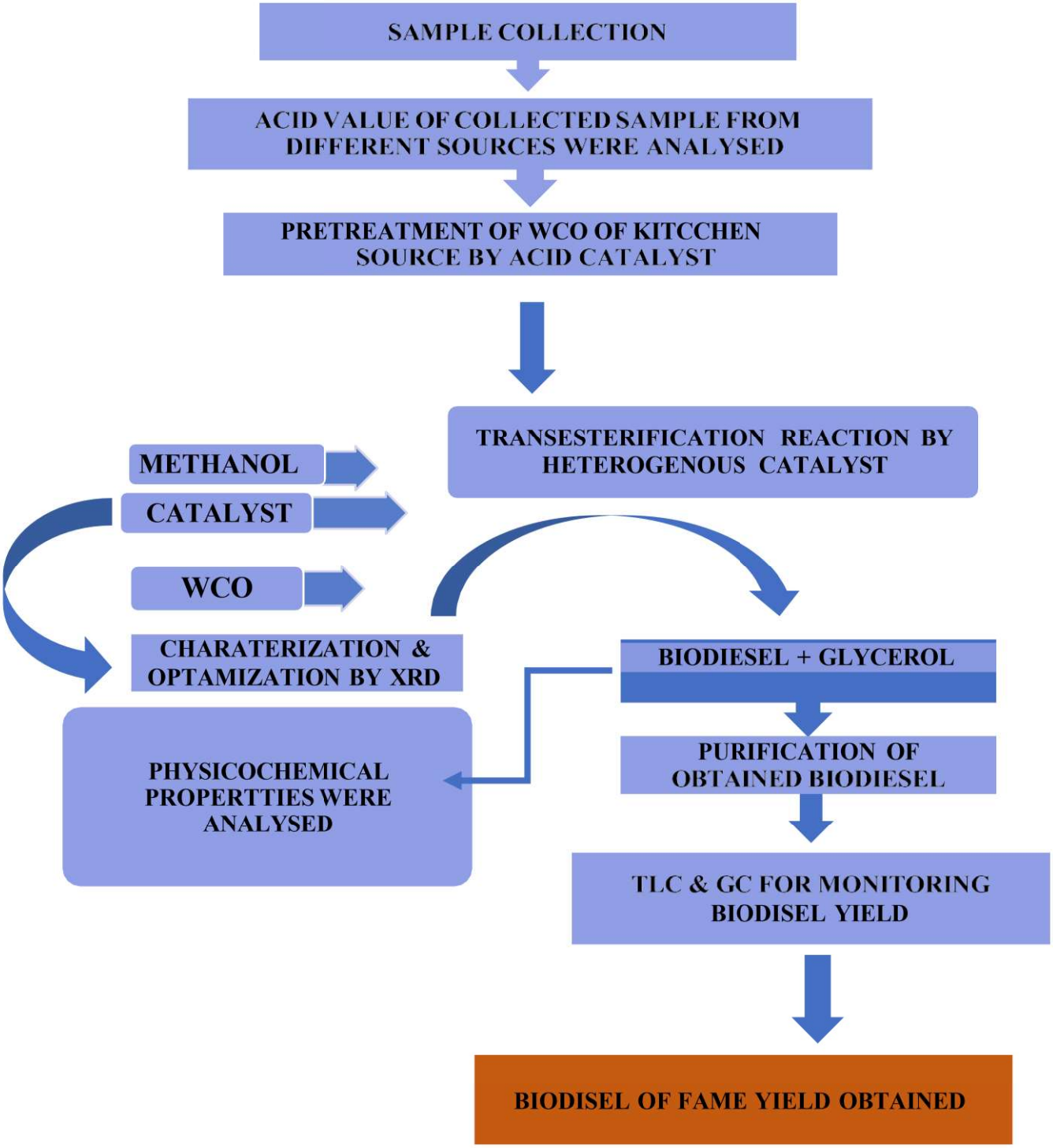
MATERIALS AND METHOD

3.1. METHODOLOGY

Biodiesel from waste cooking oil (WCO) is produced using catalytic techniques with Zn and CaO in this study. To assess WCO's suitability for conversion, physicochemical characteristics including its moisture content, free fatty acid content, saponification value, and iodine value were investigated. Acid value reduction was used to achieve esterification efficiency, while XRD study was used to characterize heterogeneous catalyst. The transesterification process was observed using Gas Chromatography-Mass Spectrometry (GC-MS) spectroscopy and thin-layer chromatography (TLC). Utilizing standard analytical methods, fuel properties such as viscosity, calorific value, cloud and pour points, flash and fire points, ash content, carbon residue, acid value, and free fatty acid content were examined in order to meet quality performance requirements. Biodiesel parameters are compared to test the working efficiency with that of diesel. The project's objective is to improve WCO's production of biodiesel in a sustainable, cost-effective, and environmentally responsible manner.

The waste cooking oil was the raw material used in conducting the study, which was previously utilized and sourced from well-known shopkeepers, house kitchens and caterers in Jhansi. This is a preferred selection because it enables the study to be based on actual waste material, thus ensuring sustainability and utilization of resources. The major chemicals used in the research were Zn (Zinc) and CaO (Calcium Oxide), methanol, KOH, HCl, which are crucial for catalysis and material synthesis. Silica gel was also used, likely as a desiccant or support material in laboratory experiments. Other essential solvents, including methanol, ethyl acetate, and hexane, were likewise employed to perform reactions, extractions, and purification. The selection of these materials reflects their significance to the research methodology of the study, particularly in catalysis, chemical processing, and analytical techniques.

PROTOCOL FOR THE BIODIESEL PRODUCTION FROM WCO



3.1.1 Sample Size

A total of 100 WCO (Waste Cooking Oil) samples were collected for this study. The sample size was determined based on a proportional stratified sampling approach to ensure representation across three major WCO-generating sources: household kitchens (45%), restaurants (35%), canteens (15%) and street vendors (5%). Each sample corresponded to a unique experimental batch, allowing one-to-one mapping between collected samples and experimental trials.

3.1.2 Sample Collection Procedure

WCO was collected from localities selected randomly within each category. From each selected point (e.g., household, restaurant), approximately 10 mL of WCO was collected weekly for 3 months. Samples were stored in airtight amber glass containers to prevent oxidation. Samples were labelled, transported to the lab, and stored at room temperature before analysis.

3.1.3 Place of Study

The survey was conducted in the Bundelkhand region of northern Indian city of Jhansi. This city was selected because of its diversified commercial, residential activity. This city is a best location to test the feasibility of utilization of waste cooking oil to prepare biodiesel as there are wide sources in this city, including restaurants, canteens, street vendors and kitchen areas in residential apartments.

3.1.4 Sample Technique

A proportional stratified sampling approach was employed to ensure adequate representation of waste cooking oil (WCO) from diverse sources across the study area. The entire population was divided into four strata based on the primary sources of WCO generation:

- Household Kitchens (45%)
- Restaurants (35%)
- Canteens (15%)
- Street Vendors (5%)

Samples were allocated proportionally to the estimated contribution of each stratum, resulting in 45 samples from households, 35 from restaurants, 15 from canteens, and 5 from street vendors, totalling 100 samples. This proportional allocation facilitated accurate representation

and enabled comparative statistical analysis of methyl ester yields across the different WCO sources.




Fig: 1.3.1. Photographs of collection of WCO Sources

Table: 3.1.- Acid value (AV mhKOH/g) results of each category samples with two replicates.

Source Category	Replicate1- Acid value	Replicate2-Acid value
Households (Kitchen)	5.7 mgKOH/g	5.6 mgKOH/g
Restaurants	5.8 mgKOH/g	5.9 mgKOH/g
Canteens	6.2 mgKOH/g	6.4 mgKOH/g
Street Vendors	6.3 mgKOH/g	6.5 mgKOH/g

Household (Kitchen) oil demonstrated the lowest acid value, indicating that it was fresher and of better quality, which in turn supported a higher biodiesel conversion efficiency. In contrast, Street Vendor oil showed the highest acid value, suggesting a greater level of degradation and consequently a reduced conversion efficiency. Oils collected from Restaurants and Canteens presented intermediate acid values, reflecting moderate quality and producing correspondingly average biodiesel yields.

3.1.5 Physicochemical properties of WCO of kitchen source

Acid value of WCO

Materials required for WCO (waste cooking oil) to perform the experiment of acid value determination. Ethanol (neutralized 95% or absolute), Phenolphthalein indicator Standardized alcoholic KOH (0.1 N), Analytical balance, Burette, pipette, conical flask, Hot plate(optional)Glass funnel, measuring cylinder

Procedure:

WCO was weighted accurately about 5 grams into a 50 mL conical flask. On Adding 25 mL of neutral ethanol to the flask. To dissolve oil completely mixture was warmed and stirred. On Adding 2–3 drops of phenolphthalein, the solution should remain colourless at this point (if acidic). Titration with 0.1 N alcoholic KOH solution from a burette until a light pink colour persists for at least 15 seconds (endpoint). Against this a bank was run in parallel which contained similar components except oil which was replaced by water. This would determine the acid value of the WCO.

Calculation:

$$\text{Acid Value (AV)} = \frac{V \times N \times 56.1}{W}$$

V = Volume of KOH used (mL)

N = Normality of KOH (usually 0.1 N)

W = Weight of oil sample (g)

56.1 = Equivalent weight of KOH

Weight of WCO sample (W) = 5.0 g

Volume of 0.1 N KOH used (V) = 5.0 mL

Normality of KOH (N) = 0.1 N

$$AV = \frac{5 \times 0.1 \times 56.1}{5}$$

= 5.61mg KOH/g

Sampling was conducted weekly over a three-month period, with consistent proportions maintained throughout the collection schedule. Within each stratum, sampling locations were selected randomly to minimize selection bias and ensure that the collected samples reflected typical WCO characteristics from each source category.

3.1.6 Saponification value of WCO

WCO (waste cooking oil) sample was used in Ethanolic KOH (0.5 N) was freshly prepared using Ethanol (95% or absolute) on adding Phenolphthalein indicator 2 -3 drops of it. Standardized HCl (0.5 N), Boiling water bath, Burette, pipette, conical flask, reflux condenser Analytical balance, Volumetric flasks, beakers, glass rod were used as materials required for the determination of saponification value.

Procedure

WCO was weighted about 5 grams into a 50 mL conical flask. On Adding 25 mL of 0.5 N ethanolic KOH to the flask that would be Attached to a reflux condenser to avoid evaporation. Mixture was heated gently on a boiling water bath for 60 minutes. It was stirred time to time to ensure complete saponification. After refluxing on adding 1–2 drops of phenolphthalein to the warm solution, the excess KOH with 0.5 N HCl was titrated until the pink colour just disappears. A blank was also run with the same volume of ethanolic KOH without oil.

Calculations:

$$SV = \frac{(B-S) \times N \times 56.1}{W}$$

Where:

B = Volume of HCl used in blank (50mL)

S = Volume of HCl used in sample (39.2mL)

N = Normality of HCl (0.5 N)

W = Weight of oil sample (5 g)

56.1 = Equivalent weight of KOH

$$SV = \frac{(50 - 23.1) \times 5 \times 56.1}{5} = \mathbf{151.17 mg\ KOH/g}$$

3.2. PRETREATMENT OF WCO OF KITCHEN SOURCE

Physicochemical parameters of waste cooking oil (WCO), such as free fatty acid (FFA) value, moisture content, saponification value, were determined to evaluate the suitability of the oil for biodiesel production. Such parameters indicate the feasibility of transesterification and biodiesel conversion with good efficiency. FFA value, moisture, saponification values are all decisive parameters that determine the pre-treatment procedure and aim to maximize biodiesel production. The findings of these measurements assist in knowing the behaviour of the oil during the production process and its ultimate fuel quality. The physicochemical properties of waste cooking oil, including acid value, moisture %, saponification value, were determined

3.2.1 Pretreatment of WCO (Kitchen source) by Acid Catalyst

Acid treatment, was applied on all the waste oil samples to achieve the lowest free fatty acid (FFA)content. Esterification with the use of homogenous acids is a commonly employed procedure in which oil was added with methanol, acid catalyst (conc. H2SO4, HCl and H3PO4) and reaction mixture was transferred to round bottom three necked flask attached with water cooled condenser placed on hot plate.

Typical reaction efficiencies of pretreatment of waste cooking oil with acid catalyst (H_2SO_4) under the specified conditions (5 wt% catalyst loading, 12:1 methanol to oil molar ratio, 60–65 °C, -hour reaction time. In a small 50ml flask, methanol at a 12:1 molar ratio (using 95% methanol) was used. To this, added 0.05 g (≈1 wt%) concentrated H_2SO_4 slowly into the methanol while stirring, ensuring that the acid should always introduced into the solvent. This produces acidified methanol (methanolic H_2SO_4). The mixture was prepared in a fume hood, with cooling applied. The 20 g of WCO is then transferred to a round-bottom flask and gently preheated to 40–50 °C to lower viscosity. The acidified methanol is added to the oil, the system is fitted with a reflux condenser, and stirring is initiated. The reaction was maintained at 60-65 °C under reflux with continuous stirring for 90 minutes, during which water and other polar byproducts are generated. After completion, the mixture was cooled to room temperature and transferred to a separatory funnel (or centrifuge) for phase separation. The upper phase consists of treated oil/methyl esters, while the lower phase contains aqueous acid residues and byproducts. The organic layer is subsequently washed with a small volume of warm deionized water to remove residual acid then dried over anhydrous sodium sulfate and filtered for further use.

Acid Value of Pretreated WCO

For acid value determination (AV), exactly 5.000 g of waste cooking oil (WCO) was weighed into a 50 mL conical flask. About 25 mL of neutralized ethanol or an ethanol/ether mixture was then added to fully dissolve the oil. Following this, 1–2 drops of phenolphthalein indicator were introduced. The sample was titrated against 0.1 N KOH until a faint pink color persisted for approximately 30 seconds, marking the endpoint. Finally, the exact volume of KOH consumed (V, in mL) was recorded for further calculations.

Calculation:

Acid value (mg KOH/g) =V×N×56.11/w

V = volume of titrant in mL,

N = normality of titrant (0.1 N),

56.11 molecular weight of KOH (mg/mmol),

W = sample mass in g (5.000 g).

$$AV=\frac{0.89\times0.1\times56.11}{5.00\ gm}$$

4.99/5 gm = 0.9986 mgKOH/g

3.2.2 Conversion of FFA

Free fatty acid (FFA) esterification was conducted using methanol and a solid acid catalyst under the optimized conditions of a 9:1 molar ratio of methanol to oil, 5 wt.% catalyst loading, h hours reaction time, and 60°C temperature. Pre- and post-reaction samples were taken to analyze the acid values. The FFA conversion was determined by comparison of the initial and final acid values through a titration method to measure the acid value of the samples. This was with the aim of lowering the content of FFA and improving the transesterification efficiency for biodiesel production.

Procedure:

The free fatty acid esterification was carried out using methanol and a solid acid catalyst under the optimized conditions (e.g., methanol-to-oil molar ratio 9:1, catalyst loading 5 wt.%,

reaction time 5 hours, and temperature 60°C). Samples were taken before and after the reaction to analyze the initial and final acid values.

FFA (%) conversion was determined by using the formula as follows:

$$\textbf{Conversion of FFA}\ (\%) = \left(\frac{A.V_{initial} - A.V_{final}}{A.V_{initial}}\right) \times 100$$

The acid value (A.V) was calculated by titrating the oil sample with a standard KOH solution and obtained from:

$$A.V = \frac{V \times 1000 \times MW \times C}{W}$$

Table:3.2.- Acid Value and FFA Conversion Before and After the Esterification Reaction

Parameter	Before Pretreatment	After Pretreatment
Acid Value (mg KOH/g)	5.61	**0.9**
FFA (%)	2.82%	**0.45%**
FFA conversion rate	——	**Approx. 84%**

Table: 3.2. presents the acid value and FFA conversion prior and subsequent to the transesterification reaction. Prior to the reaction, the acid value was 5.61 mg KOH/g, signifying a greater amount of free fatty acids in the waste cooking oil (WCO). Following the reaction, the acid value decreased to 0.9mg KOH/g, and the FFA conversion was 83.95%. This considerable decrease in acid value and the excellent FFA conversion percentage show how effective the process of esterification is in decreasing free fatty acids and converting the oil to biodiesel.

It indicates the reduction of the free fatty acid with increasing time, which is in line with the decrease in acid value. The high rate of conversion (83.95%) is an indication that the reaction had successfully converted the majority of the free fatty acids.

3.3. TRANSESTERIFICATION REACTION OF PRETREATED WCO USING HETEROGENOUS CATALYST

The wet impregnation approach was used to create the Nano-crystalline Zn/CaO catalyst. First, 40 millilitres of deionized water were used to disperse CaO to create a suspension. To obtain Zn loading between 1.5 and 5 weight percent in CaO, 10 millilitres of an aqueous zinc sulphate solution were added to this suspension at different concentrations. After that, the mixture was agitated to guarantee that the zinc was evenly distributed throughout the CaO matrix. The final catalyst was obtained by calcining the resultant slurry at 700°C for four hours in a muffle furnace after it had been well mixed and dried. The catalyst that was produced was called x-Zn/CaO-T, where "x" stands for the weight percentage of Zn and "T" for the calcination temperature. To guarantee the development of Nano-crystalline properties, the procedure required exact control over composition and thermal treatment.

3.3.1 Catalyst Preparation

Wet impregnation was used to create the nanocrystalline Zn/CaO. Prepared Zinc Sulphate Solution weighing accurately $ZnSO_4$. $7H_2O$ to match the desired doping level (0.075g for 1.5% to 0.350g for 7%). Dissolved it in 10 mL of deionized water to form a clear zinc sulphate solution. Taking 5 g of CaO and suspend it in 40 mL of deionized water in a 100 mL beaker. Stirred continuously using a glass rod or magnetic stirrer to form a homogenous slurry. Slowly added the zinc sulphate solution into the CaO suspension while stirring. While continued stirring for 2–3 hours at room temperature for uniform dispersion of Zn^{2+} ions onto CaO particles. After stirring, mixture settled, and dried in an oven at 110°C for 12 hours to remove moisture. The dry mixture was then calcined for four hours at 700°C in a muffle furnace. The catalyst that was produced was called x-Zn/Cao-T, where x and T stand for the weight percentage of Zn and the calcination temperature, respectively.

3.3.2 XRD experiment

The heterogeneous catalyst's structural, morphological, and elemental properties had to be ascertained using a variety of analytical methods. XRD analysis was carried out with a 40 kV PANalytical X'Pert Pro diffractometer that utilized nickel-filtered monochromatic Cu K radiation with a scan rate of 2°/min in the 2 range of 5–80°. This method was used to investigate the crystallinity and phase composition of the catalyst and reusability under controlled temperature and gases.

Calcium oxide (CaO) and zinc-modified CaO catalysts (1.5%, 3%, 5%, and 7% Zn/CaO) were synthesized via wet impregnation method. Calcium carbonate (analytical grade), zinc sulphate hexahydrate ($Zn(SO_4)_2 \cdot 6H_2O$), and deionized water. The synthesized catalyst powders were finely ground using an agitate mortar and pestle to obtain uniform particle size. The samples were dried at 100 °C for 2 hours and stored in airtight containers prior to XRD analysis. PANalytical"s Pert Pro diffractometer" with 40 kV maintaining nickel filtered monochromatic Cu Kα radiation was employed for the analysis of X-ray diffraction pattern. The catalyst was analyzed over a 2θ range of 5–80° at a scanning rate of 2°/min.

Procedure:

Powder method also called Debye Scherrer method showed XRD patterns were measured to investigate the influence of Zn doping on the structure of CaO. By varying the Zn concentration (1.5wt% -7wt%) comparison between both samples were observed. The CaO exhibited cubic phase and no distinct crystalline peak of ZnO phase observed as long as the concentration of Zn doped remain till 5wt%, this could be attributed to the formation of Zn/CaO in a single cubic phase. There would be further increase in Zn concentration >5wt% that leads to decrease in lattice strain would lead to decrease in catalytic performance. The sizes of crystallites were estimated using Scherrer's formula:

Data and Calculation:

Crystallite sizes in CaO and Zn-doped CaO samples were calculated using Scherrer's formula

$$D = \frac{K\lambda}{\beta \cos\theta}$$

D (*or* τ) – The average crystallite size (nm).

K –The shape factor (dimensionless), typically ≈ 0.9 (range 0.8–1.0).

λ – The X-ray wavelength, usually in nanometres (e.g., Cu Kα = 0.154 nm).

β – The peak broadening at full width at half maximum (FWHM), measured in radians,

θ – the Bragg angle, which is half the diffraction angle (2θ) for the peak—also in radians in the denominator term

3.4. WCO CONVERSION IN TO BIODIESEL (TRANSESTERIFICATION)

Pretreated waste cooking oil was subjected to transesterification in a 250 mL three-neck round-

bottom flask fitted with an oil bath, magnetic stirrer, and water-cooled reflux condenser. The reaction was carried out at a controlled temperature of 60–65 °C using 20 g of waste cooking oil, methanol (95% v/v) at a 12:1 molar ratio, and 5 wt% of Zn-doped CaO catalyst under continuous stirring. The catalyst was synthesized by doping Zn onto CaO to achieve nano crystallinity.

Nanocrystalline Zn/CaO was prepared via wet impregnation. Accurately weighed zinc sulfate heptahydrate ($ZnSO_4 \cdot 7H_2O$, 0.075 g for 1.5% to 0.350 g for 7% doping level) was dissolved in 10 mL of deionized water to form a clear zinc sulfate solution. Separately, 5 g of CaO was suspended in 40 mL of deionized water in a 250 mL beaker and stirred to obtain a uniform slurry. The zinc sulfate solution was then added dropwise to the CaO suspension under continuous stirring, which was maintained for 2–3 hours at room temperature to ensure homogeneous dispersion of Zn^{2+} ions onto the CaO particles. The resulting mixture was allowed to settle, oven-dried at 110 °C for 12 hours, and subsequently calcined at 700 °C for 4 hours in a muffle furnace.

After completion of the transesterification reaction, the mixture was transferred to a separating funnel and left overnight, allowing the biodiesel layer to separate from the glycerol phase.

3.5. PURIFICATION OF BIODIESEL

The biodiesel obtained from the transesterification reaction was purified to remove residual catalyst, unreacted methanol, and soap content. Both wet and dry washing techniques were employed to ensure a clean final product. In the wet washing process, biodiesel was repeatedly washed with water preheated to 60 °C until a clear and distinct biodiesel layer was obtained. The washed biodiesel was then dried by heating at 100 °C to eliminate any remaining moisture.

For the dry washing method, silica was used as an adsorbent to remove impurities. Approximately 5 wt% silica was added to the biodiesel and the mixture was gently stirred at 60 °C for two hours. The mixture was then allowed to stand, enabling the silica to settle at the bottom. Finally, the purified biodiesel was carefully separated from the settled adsorbent.

3.6. METHODS AND EQUIPMENT USED FOR MONITORING THE TRANSESTERIFICATION PROGRESS AS FOLLOWS: -

The reaction of transesterification was tracked by Thin Layer Chromatography (TLC) and Gas Chromatography-Mass Spectrometry (GC-MS). TLC, a rapid and cost-effective qualitative analysis technique, was used for tracking reaction completion. Every 15 minutes, samples were withdrawn, centrifuged to split the catalyst, and the liquid phase was diluted with a hexane/ethyl acetate (90:10 v/v) mobile phase on silica gel stationary phase. Formation of biodiesel was confirmed by comparing the Retention Factor (Rf) values with a reference methyl oleate. Following initial confirmation by TLC, additional analysis was conducted using GC-MS to accurately identify and quantify the FAME components. The GC-MS analysis was conducted using a capillary column, with helium as the carrier gas, and temperature programming from 60°C to 300°C. The resultant chromatogram yielded typical peaks for methyl esters, demonstrating the successful production of biodiesel from waste cooking oil. The synergistic combination of TLC and GC-MS facilitated precise monitoring of biodiesel formation and analysis of conversion efficiency.

3.6.1 Thin Layer Chromatography (TLC)

Thin Layer Chromatography (TLC) was utilized to follow the transesterification reaction. Samples from the reaction mixture were every 15 minutes taken out, centrifuged to get rid of the catalyst, and the resulting supernatant was analyzed using TLC. The mobile phase used was hexane/ethyl acetate in the ratio of 90:10 (v/v), and silica gel plates were employed as the stationary phase. Samples were placed alongside a reference methyl oleate sample for comparison to enable qualitative validation of the biodiesel production process.

Procedure:

Thin Layer Chromatography (TLC) was employed to track the transesterification reaction progress. Every 15 minutes, a little reaction mixture was drawn up with a dropper, centrifuged to remove the catalyst, and the resulting supernatant taken for TLC analysis. Hexane/ethyl acetate in a 90:10 (v/v) ratio served as the mobile phase, and silica gel plates served as the stationary phase. The samples were spotted along with a standard sample of methyl oleate for comparison.

Observation:

The spot of the corresponding standard methyl oleate (biodiesel) appeared, indicating the formation of FAME (Fatty Acid Methyl Ester). The Rf values of the sample and the standard were compared.

Table: 3.3.- Retention Factor (Rf) Values for Biodiesel Confirmation by Thin Layer Chromatography

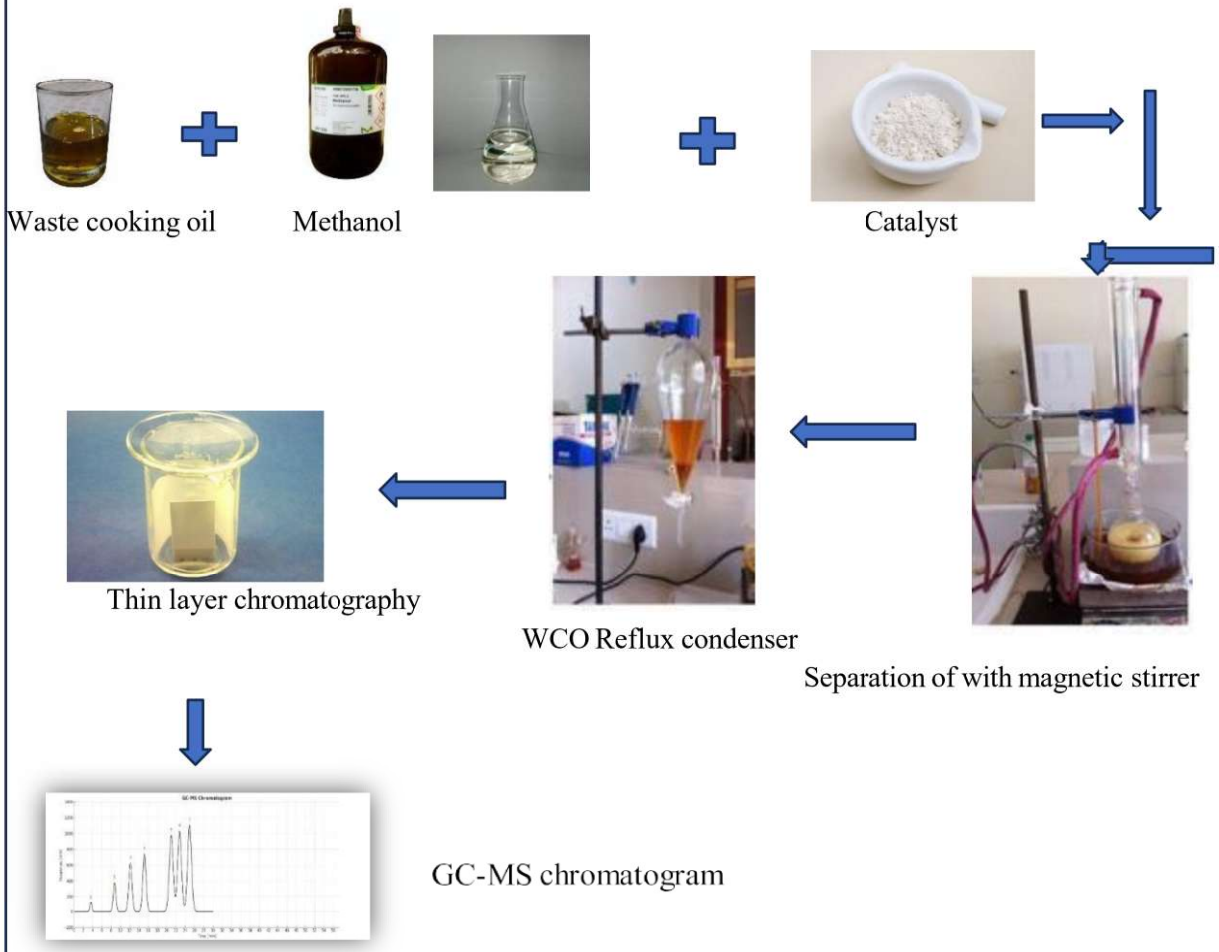
Sample	Solvent System	Rf Value
Standard Methyl Oleate	Hexane: Ethyl Acetate (90:10)	0.73
Biodiesel Sample	Hexane: Ethyl Acetate (90:10)	0.72

As indicated in Table 3.3, the Rf value for the biodiesel sample (0.72) was very close to the Rf value of the standard methyl oleate (0.73) when a hexane: ethyl acetate (90:10) solvent system was used. This close similarity verified the successful synthesis of Fatty Acid Methyl Esters (FAMEs) in the process of transesterification. Thin Layer Chromatography was therefore a rapid and efficient means of qualitatively confirming biodiesel production.

Three samples were taken to analyse conversion of WCO in to biodiesel. Waste Cooking Oil Sample Dissolving a small amount (~5 mg) of the WCO in a few mL of hexane. Biodiesel Sample was Dissolved in a similar amount in same solvent. Standard sample was Prepared of methyl oleate whose retention factor (0.65 to 0.80) to be known.

By Drawing a pencil line 1 cm from the top and bottom of the TLC plate. Capillary tube was used to spot each sample just above the line denoted as bottom line then spots were dried. Mobile phase (Hexane: Ethyl acetate 90:10 v/v) was poured into the beaker to a depth of ~0.5 cm. TLC plate was placed upright in the beaker (spots above solvent level) then beaker was covered by foil and allow the solvent front to rise. Samples run were removed and measurements were taken using scale for retention factor.

Fig: 1.4.- Schematic Diagram for Biodiesel Production setup below



Observation:

Retention factor for three samples was calculated-

$$\mathbf{Rf} = \frac{\text{Distance travelled by the solvent front}}{\text{Distance travelled by the sample}}$$

The amount of biodiesel produced was calculated by comparing its retention factor with that of the reference methyl oleate ($C_{19}H_{32}O_2$), as shown in figure 4.5. Utilizing 1GC-MS, the resulting methyl ester of free fatty acids was characterized.

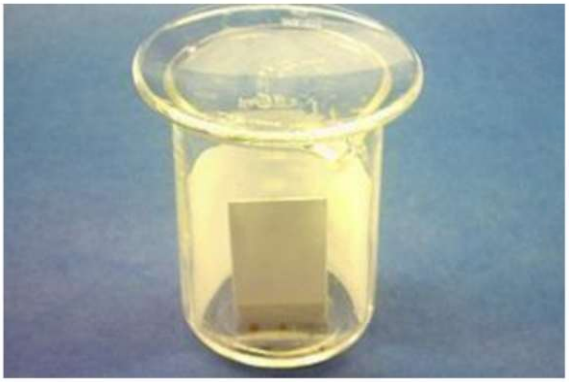


Figure: 1.5.- TLC examination of the following: (A) Waste cooking oil, (B) Biodiesel generated from waste cooking oil, and (C) Methyl oleate standard

3.6.2 Gas Chromatography-Mass Spectrometry (GC-MS)

Gas Chromatography-Mass Spectrometry, is a versatile analytical technique that combines the separation technique of gas chromatography (GC) that detects and identifies the ability to perform qualitative and quantitate analysis using mass spectrometry (MS). It's used to analyse complex mixtures by separating the components based on their physical and chemical properties, then identifying each component based on its mass and fragmentation pattern.

Gas Chromatography separate the mixture of components. It involves injecting gaseous/liquid samples in to solvent system that acts as a carrier gas or mobile phase. This gas then passes through the stationary phase. The temperature of the injector is maintained at 250°C, and the carrier gas used helium under a constant flow rate of 1.0 mL/min. Stationary phase inside the column of GC is filled with liquid/solid substance with high boiling point up to temperature (2000°C). The oven temperature is programmed from 60°C (held for 2 minutes) to 450°C with a rate of 10°C/min. The sample of biodiesel is diluted in hexane for analysis.

Sample moves to detector for identification in Mass Spectroscopy Electron ionization chamber where they are bombarded with electrons to become ionized. Certain ions undergo fragmentation into smaller ions, which are then separated according to their mass-to-charge ratio (m/z). These ions are subsequently detected, and their relative abundance is measured to produce a mass spectrum. The GC-MS analysis indicated that the WCO produced biodiesel would be a viable fuel source and an alternative to diesel fuel. WCO offers similar characteristics that represent reducing reliance on non -renewable energy source of fuel and transitioning towards more sustainable energy solution.

Instrumentation and Conditions

The GC-MS analysis was performed using an Agilent 7890B gas chromatograph coupled with a 5977A mass spectrometer. The FAMEs were separated on a DB-WAX capillary column (30 m × 0.25 mm ID × 0.25 μm film thickness). The operational parameters were as follows:

- **Carrier Gas:** Helium at a constant flow rate of 1.0 mL/min
- **Injection Volume:** 1 μL (split ratio 10:1)
- **Oven Temperature Program:**
    - Initial temperature at 60°C (held for 2 min)
    - Increased to 350°C at 10°C/min
    - Final ramp to 400°C at 5°C/min (held for 10 min)
- **Injector Temperature:** 250°C
- **MS Conditions:** Electron Ionization (EI) mode at 70 eV, scan range 50–550 m/z
- **IS standard -**Palmitic acid Molecular weight= 650, mass=1mg in sample(biodiesel) 20mg of weight.

Sample Preparation

The biodiesel sample was diluted in n-hexane to a concentration of 20 mg/mL and filtered through a 0.45 μm syringe filter before injection. A known standard mixture of FAMEs (palmitic acid) was also injected to identify and quantify individual components by comparing their retention times and mass spectral data.

The GC-MS chromatogram of the biodiesel sample (Figure 4.6) showed distinct peaks corresponding to common FAMEs such as methyl hexadecaoate (C16:0), methyl stearate (C18:0), methyl oleate (C18:1) and methyl linoleate (C18:2). These components were identified by matching their mass fragmentation patterns with the NIST library database.

Calculation of Methyl Ester Content Using GC-MS Technique

The methyl ester content of the biodiesel sample was calculated based on the area percentage obtained from GC-MS analysis, using the following formula:

$$\text{Methyl Ester Content (\%)} = \frac{\text{Methyl Ester Area (\%)} \times \text{Weight of the Product (g)}}{\text{Weight of the feedstock used(g)}}$$

Methyl Ester Area (%) = 97.52
Weight of the Product = 16.9 g
Weight of the Feedstock = 20 g

Calculation:

$$\text{Methyl ester \%} = \frac{97.52 \times 16.9}{20} = 1647.088$$
$$= 1647.088 / 20 = 82.3544$$

Result: The methyl ester content of the biodiesel sample was **82.35%**.

3.7. METHODS AND EQUIPMENT USED FOR DETERMINATION OF FUEL PROPERTIES

The biodiesel fuel properties were analyzed by utilizing standardized analytical tests to assess compatibility with engine performance and conformity with traditional fuel quality standards. Kinematic viscosity, which quantifies the resistance of the fuel to flow, was analyzed since it has a direct effect on fuel injection efficiency; very high viscosity can result in clogging of the injectors, while low viscosity can cause leakage and low combustion efficiency. The calorific value (CV), representing the total energy released during combustion, was determined to assess the energy content of the biodiesel, which is crucial for power generation.

Cloud point (CP) and pour point (PP) were tested to determine the low-temperature behaviour of biodiesel. CP is the temperature at which wax crystals start to develop, making the fuel cloudy, and PP is the lowest temperature at which the fuel can still be poured. Flash point (FP) and fire point (FPt) tests were performed in order to identify the lowest temperatures at which the fuel vapours can be ignited in the presence of an ignition source in the safe storage, handling, and transportation of biodiesel.

Ash content was measured with an electric muffle furnace at 500°C in order to measure the amount of residual inorganic material, including sodium, potassium, and calcium, that can affect combustion quality and engine deposits. Carbon residue analysis, as per ASTM D169/IP 13 standards, tested the fuel's tendency to produce carbon deposits as a measure of combustion

stability. The acid number (AV) was determined by titration with potassium hydroxide (KOH) in order to measure the free fatty acid (FFA) content that affects fuel corrosiveness and engine wear. Lastly, the FFA content was independently established by a method of titration using ethanol and diethyl ether since excessive FFA content can result in soap formation during the biodiesel manufacturing process and adversely affect the transesterification process.

3.7.1 Kinematic Viscosity

Kinematic viscosity was measured by a viscometer at 40°C according to ASTM D445 standards. In this process, a specified volume of biodiesel was permitted to flow under gravity through a calibrated capillary tube. The time taken by the biodiesel to flow through the tube containing two bulb was measured, and this flow time was utilized to calculate the kinematic viscosity of biodiesel. The kinematic viscosity is important since it influences the way the fuel moves through the fuel injection system and directly impacts engine performance.

Procedure:

Clean and dry the viscometer to charge the sample in to it. By inverting the instrument, suction was applied to the large tube and immersing small tube in to biodiesel sample to draw the liquid up to second mark of the tube. Now turn the instrument in to its normal vertical position. viscometer was placed in to the holder and inserted in to constant temperature bath. Sample was allowed to come to temperature at 40^{o} C for 10 min. When suction was applied to the large tube bulb the liquid slightly moves towards the top mark of small bulb. Stopwatch was kept to measure the time and allow the liquid sample to flow freely down till the second mark.

Time was measured between both the mark to calculate viscosity. This process was repeated 2 times to take an average measurement using petroleum diesel viscosity 4.26mm2/s as a reference standard.

Record the time and calculate the kinematic viscosity.

$$V = Ct$$

where, V is kinetic viscosity (centistoke, cSt), C is calibration factor of the bulb of the viscometer tube used for testing (cSt/s) = 0.025mm2/s2 and t is the time (s).

Observation:

Liquid samples	Time of flow (sec)	Mean time (sec)	Kinematic viscosity
Petroleum diesel	1.8, 2.2, 1.6	1.8	180 x 0.025= 4.5
produced biodiesel	1.9, 2.5, 2.3	2.233	223 x 0.025= 5.57

Table: **3.4.-** Observation of Kinematic Viscosity of produced Biodiesel

The biodiesel product has a kinematic viscosity of 5.57 mm^2/s (cSt), as seen in Table 3.5. This figure is within the recommended limit for the biodiesel standard, making the biodiesel run efficiently in a diesel engine. The best viscosity is important to achieve good fuel injection performance, as this allows proper atomization and smooth combustion. Very high viscosity will cause clogging of the injector, poor fuel flow, and excessive friction within the fuel system, whereas low viscosity will create leakage and loss of fuel, making the engine inefficient. Thus, having a perfect viscosity is vital to secure the performance of the biodiesel and the durability of the engine.

Table 3.5: Kinematic Viscosity of Produced Biodiesel

Property	**Value**	**Unit**
Kinematic Viscosity	5.57	mm^2/s (cSt)

As indicated in Table 3.5, the kinematic viscosity of the yield biodiesel was found to be 5.57mm^2/s (cSt) at 40°C, a value within the acceptable limits set for the standards of biodiesel. This optimal viscosity provides easy fuel injection, good atomization, and smooth burning in diesel engines, reducing dangers of clogging of the injector or leakage of fuel.

3.7.2 Calorific Value

Calorific value may be regarded as the heat energy evolved due to the complete combustion of a specified quantity of fuel and its combustion product returned to its original temperature of combustible mixture. It is one of the key parameters employed for the measurement of energy content of a fuel. Thus, CV is the fundamental power characteristic of a fuel quality.

Procedure:

The calorific value of the biodiesel produced was measured in a bomb calorimeter according to the ASTM D240 standard test method. During this process, the appropriate amount of biodiesel 5g was weighed to crucible and loaded into an airtight container to which electrodes were attached referred to as a bomb, which has an oxygen (25-30 atm pressure) supply system for complete combustion. The bomb was then placed inside calorimeter containing known amount of water. Initial temperature was measured as t1 and apparatus was fully covered with a lid. Electrode were then connected with 6V battery. As the electric current passed, fuel burned and heat released was transferred to surrounding water. The rise in the water temperature was precisely measured as t2 and used to determine energy released per unit mass of the biodiesel. This is an accurate way to measure the overall energy content of the fuel that is required in order to determine its feasibility as an alternative source of fuel.

Calculation:

$T1 = 29^{o}C$, $T2 = 48 \circ C$ $T1 - T2 = \Delta T$

$\Delta T = 19^{\circ}C$

$Cw = 10{,}000\ J/\circ C$ (Heat capacity of calorimeter)

$m = 5$ gm (weight of the sample)

$$\text{calorific value} = \frac{(Cw \times \Delta T)}{m}$$

$$\text{Calorific Value} = \frac{10{,}000 \times 19}{5} = 38{,}000\ J$$

Convert to MJ/kg: = 38MJ/kg

It indicates that the calorific value of the biodiesel manufactured was 38 MJ/kg. This high calorific value is an indicator that the biodiesel has high energy content, which is a very important consideration in its use as a fuel. A higher calorific value means higher energy efficiency, i.e., the biodiesel is capable of generating more power when burned in diesel engines. With this energy production, the biodiesel proves its potential as a viable and cost competitive replacement for traditional fossil fuels, while playing its role in sustainable energy solutions without undermining engine performance.

3.7.3 Cloud Point and Pour Point

The cloud point and pour point of the resulting biodiesel were identified following ASTM D2500 and ASTM D97, respectively, standards using the cooling bath procedure. In the process, a sample of the biodiesel was cooled at a regulated rate within a bath. The cloud point was measured as the temperature decreased on which wax crystal first appeared to make the fuel cloudy. The pour point was defined as the lowest temperature at which the fuel was liquid and could flow freely. The sample was monitored at different temperature intervals, and the temperatures at which these events took place were recorded.

Procedure:

Cloud point and pour point of the biodiesel produced were found as per the ASTM D2500 and ASTM D97 standards, respectively, by a cooling bath method. In that process, a biodiesel sample was cooled under controlled bath with constant rate. Initial temperature of thermometer was maintained at 20^{O} C. Cloud or haze was appeared after sometime on shaking the sample this temperature was noted as cloud point. Left the sample to drop the temperature till 3^{O} C. Sample does not move but slight movement in the sample measured the reading of pour point.

Observation:

As evident from Table 3.6, the cloud point of the resultant biodiesel was 5°C and the pour point was 2°C. These measurements signify that the biodiesel has satisfactory flow characteristics at reasonably low temperatures. The fairly low cloud point implies that the biodiesel should experience some wax deposition during cold weather but is capable of flowing easily at slightly more than freezing temperature. The pour point of 2°C suggests that the biodiesel can be kept in a fluid form and flow in moderately cold weather. It is ideal for applications in areas with moderate to mild winter climates, without posing any serious danger of fuel gelling or flow problems, to provide effective performance under those conditions.

Table: 3.6.- and figure: 1.6.- Cloud Point and Pour Point of Produced Biodiesel with picture

Property	Value	Unit
Cloud Point	5	°C
Pour Point	2	°C



As indicated by Table 3.6, the resulting biodiesel had a cloud point of 5°C and a pour point of 2°C.

3.7.4 Flash point and fire point

The fire point and flash point of the resulting biodiesel were ascertained with a Pensky-Martens closed cup tester, in accordance with ASTM D93. A biodiesel sample was loaded into a sealed cup, which was then heated in a controlled setting. An ignition source was applied at uniform temperature intervals, and the temperature at which the fuel vapours ignited (flash point) and continued to burn (fire point) was measured. The flash point defines the lowest temperature at which the fuel vapours produce enough vapor to form an ignitable mixture with air, while the fire point is the temperature at which the fuel continues to burn once ignited. The process gives safe measurement of the combustion properties of the fuel for its handling, storage, and transportation.

Procedure:

The flash point and fire point of the resulting biodiesel were established through a Pensky-Martens closed cup tester, according to ASTM D93. In the test, a tiny amount of biodiesel is poured into an enclosed cup, and the cup is heated under a controlled environment. A source of ignition is used (match stick) at standard temperature intervals, and the temperature at which the fuel vapours ignite (flash point) and after approx10^{O} C temperature oil continued to burn that represent (fire point) was noted. The flash point is the lowest temperature at which the fuel gives off sufficient vapor to create a flammable mixture with air (initial burning temperature, and the fire point is the temperature at which the fuel will continue to burn once ignited. This process guarantees that the combustion properties of the fuel are quantified safely for transportation, storage, and handling.

Observation:

As indicated in Table 3.7, the flash and fire points of the biodiesel produced were 152°C and 164°C, respectively. These are high figures, which signify that the biodiesel has good safety properties, meaning that it is safer to handle, store, and transport than traditional petroleum diesel. These findings considerably minimize the chances of the biodiesel igniting accidentally and guarantee that the biodiesel is safe to use in most environments

Table 3.7 and figure: 1.7.- Flash Point and Fire Point of Produced Biodiesel with picture

Property	Value	Unit
Flash Point	152	°C
Fire Point	164	°C



Table 3.7 indicates that the biodiesel produced has a flash point of 152°C and a fire point of 164°C. These are high values that reflect very good safety properties for handling, storage, and transport, greatly minimizing the chances of accidental ignition over conventional petroleum diesel.

3.7.5 Ash Content

The ash content of the resulting biodiesel was found by burning a known amount of the biodiesel sample in a muffle furnace at 500°C. The biodiesel sample was put into a pre-weighed crucible, and the furnace was heated to completely burn all organic matter. Once the combustion process was finished, the inorganic residue left behind was weighed. This waste, mostly metallic salts and ions, is the non-burning part of the fuel. Then the ash value was determined by comparing the residue weight with the original sample weight, as a percentage.

Procedure:

The ash content of the resultant biodiesel was ascertained by burning a known amount of the sample of biodiesel in a muffle furnace at 500°C. The sample was put in a pre-weighted crucible, and the furnace was brought to the desired temperature to incinerate all the organic content. Once the combustion was finished, the left-inorganic residue in the crucible was weighed. This remaining ash, which is mostly metal salts and ions, is the non-combustible part of the fuel. The ash percentage was then determined by the formula given, which is the comparison of the residue weight to the original weight of the sample, in percentage.

Observation:

As evident from Table 3.8, the ash percentage of the resulting biodiesel was 0.02% w/w. Such a low ash percentage demonstrates that the biodiesel is extremely pure with very little inorganic impurities. Low ash percentage indicates that the biodiesel will leave minimal ash after combustion, with less chance of engine deposits and less maintenance required. This property

is essential for engine operation, since too much ash can cause wear, corrosion, and decreased efficiency in the long run.

Table: 3.8.- Ash Content of Produced Biodiesel

Property	Value	Unit
Ash Content	0.02	% w/w

Ash content was determined by the following given equation:

$$A_s = \frac{W_\propto}{W_s} X100$$

As shown in Table 3.8, the ash content of the resulting biodiesel was found to be 0.02% w/w. This extremely low ash content reflects high fuel purity and implies that the biodiesel will leave very little inorganic deposits upon combustion, thereby improving engine life and performance.

3.7.6 Carbon Residue Test

The carbon residue of the resulting biodiesel was determined by using the Conradson carbon residue apparatus, according to ASTM D189. A given quantity of biodiesel was put under destructive distillation in a crucible, where it was raised to a high temperature (about 500°C) to mimic the conditions of combustion. Heating destroyed the fuel constituents, enabling measurement of the fuel's tendency to deposit carbon (coke). Following the heating time, the carbon residue that was left was cooled in a desiccator and measured. The percentage of carbon residue was obtained by dividing the residue weight by the initial sample weight, giving an indication of the fuel's ability to foul engines.

Procedure:

The carbon residue of the resulting biodiesel was analyzed with the Conradson carbon residue apparatus, according to ASTM D189 standards. For this procedure, a measured amount of biodiesel underwent a destructive distillation in a crucible. The sample was heated at a high temperature, usually about 500°C, to disintegrate the fuel components. This procedure replicates the conditions of combustion within an engine, enabling measurement of the fuel's propensity to deposit carbon (coke). Once the heating was complete, the residue left behind, which was made up of carbon, was cooled in a desiccator and weighed. The percentage of

carbon residue was determined by dividing the weight of the residue by the original sample weight, offering a measure of the potential of the fuel to foul engines.

Observation:

As indicated in Table 3.9, the carbon residue of the resulting biodiesel was found to be 0.04%. This small percentage reveals that the biodiesel has less tendency to create carbon deposits (coke) when burned. The smaller percentage of carbon residue is preferred, which indicates that the biodiesel will lead to cleaner engine performance with less chances of carbon accumulation in the engine components. This is good for long-term maintenance and engine performance, as carbon build-up can over time cause clogging, cut efficiency, and result in damage to the engine.

Table: 3.9.- Carbon Residue Percentage in Produced Biodiesel

Property	Value	Unit
Carbon Residue	0.04	%

Percentage of residue by carbon is determined by the formula which is as follows:

$$C_r = \frac{W_c}{W_s} X100$$

Table 3.10 indicates that the carbon residue content of the biodiesel produced was 0.04%. This is a low level which means there is little tendency towards coke or carbon deposit formation on combustion, and hence it is clear that the biodiesel would ensure cleaner engine running and less maintenance problems. `

3.7.7 Acid Value

The acid value of the biodiesel was measured using titration of a standardized potassium hydroxide (KOH) solution. The biodiesel sample 20gm was mixed with a solvent in a 1:1 ratio of diethyl ether and 95% ethanol (neutralized with titrant) and 2-3 drops of the indicator used was phenolphthalein (0.5% solution in ethanol). Titration was achieved by adding 0.1M KOH in ethanol solution dropwise until endpoint, which consisted of a long-lasting pink colour for at least 30 seconds, reflecting that the free fatty acids (FFAs) have been fully neutralized. 250ml conical flask, 50 ml burette, pipettes, balance were used as glassware's. Calculating the acid

value was from the quantity of KOH utilized to neutralize the sample to determine the level of acid contained in the biodiesel.

Procedure:

The acid value of the biodiesel produced was found by titrating the biodiesel sample with a standard potassium hydroxide (KOH) solution. The process entailed measuring a known volume of the biodiesel sample and adding it to a conical flask. The sample was then combined with 25 mL of a solvent made up of a 1:1 mixture of diethyl ether and 95% ethanol. Phenolphthalein was employed as an indicator to visually determine the endpoint of titration. 0.1 N alc. KOH solution (Taking just 1.6 mL from that 100 mL stock solution to titrate 20 g biodiesel sample) was added slowly to the biodiesel sample until the pink colour lasted for at least 30 seconds, which signifies complete neutralization of FFAs in the biodiesel. The acid value was then determined based on the formula given, connecting the quantity of KOH needed to neutralize the sample to its acid content.

Observation:

Here are the observation table and calculation using 1.6 mL of titrant volume (0.1 M KOH Ethanol):

Table: 3.10- Acid Value Determination of Produced Biodiesel

S. No.	Weight of Sample (g)	Burette Initial (mL)	Burette Final (mL)	Volume of KOH Used (mL)	Normality of KOH (N)
1	20.00	0.00	1.60	1.60	0.1
2	20.00	0.00	1.60	1.60	0.1
3	20.00	0.00	1.60	1.60	0.1

V = 1.60V = 1.60 mL

N = 0.1N

W = 20.00W = 20.00 g

56.1 = Equivalent weight of KOH

The calculation formula for the determination of acid number is:

$$\textbf{Acid Value} = \frac{\textbf{56.1 X Normality of KOH solution X volume of KOH used}}{\textbf{Weight of sample taken}}$$

$$\text{Acid Value} = \frac{1.6 \times 0.1 \times 56.1}{20} = \frac{8.976}{20} = 0.4485 \text{ mg KOH/g}$$

The acid value of the biodiesel sample is 0.44 mg KOH/g using 1.6 mL of 0.1 M KOH for 20 g of biodiesel.

As indicated by Table 3.10, the acid value of the produced biodiesel was 0.44 mg KOH/g. This low acid value is indicative of low free fatty acids (FFAs) in the biodiesel, and this is beneficial since high FFAs may contribute to fuel corrosiveness and wear on the engine. The outcome indicates that the biodiesel has good quality and will not play a significant role in corrosion and wear on the engine components.

3.7.8 Free Fatty Acid (FFA content)

Free Fatty Acid (FFA) content of the biodiesel produced was measured using a titration technique. A measured amount of biodiesel was initially combined with ethanol in order to dissolve the sample, and the solution was heated to complete dissolution and reaction of free fatty acids. The sample of biodiesel was then titrated against a 0.1N KOH in the presence of an indicator, phenolphthalein. The titration was continued until the endpoint, which was marked by a steady pink colour, indicating neutralization of the free fatty acids by the KOH. The FFA content was then calculated from the amount of titrant consumed, giving a percentage of FFA in the sample.

Procedure:

The Free Fatty Acid (FFA) level of the produced biodiesel was found by a titration technique. The procedure involved mixing a known volume of biodiesel with ethanol to dissolve the sample. The solution was heated to a moderate temperature in order to achieve complete dissolution and reaction of the free fatty acids. Following this, the biodiesel sample was titrated against a 0.1N KOH solution with the use of phenolphthalein as the indicator. Titration proceeded to the endpoint where there was a permanent pink color, which signals the neutralization of the free fatty acids with the KOH. The FFA percentage was calculated by

applying the given equation to the volume of titrant consumed and the weight of the sample of biodiesel, yielding a percentage of FFA in the sample.

Observation:

As indicated in Table 3.11, the FFA content of the resulting biodiesel was found to be 0.20%. The low FFA content suggests that the biodiesel production process was successful and that the potential for saponification, which can interfere with the transesterification reaction, was eliminated. High FFA content leads to unwanted side reactions and to the production of soaps, which are detrimental to biodiesel quality and production efficiency. Hence, the low FFA level indicates that the biodiesel is of superior quality, guaranteeing improved engine performance and prolonged engine life through reduced free fatty acid corrosiveness.

Table: 3.11.- Free Fatty Acid (FFA) Content of Produced Biodiesel

Parameter	Value
Acid Value	0.4485 mg KOH/g
Free Fatty Acid (FFA) %	0.205%

$$\boldsymbol{FFA}(\%) = \frac{(\boldsymbol{ml\ of\ titrant}) \times (\boldsymbol{Neutrslity\ of\ titrant}) \times \mathbf{25.6}}{\boldsymbol{Weight\ of\ sample\ in\ gm.}}$$

$$\text{FFA } \% = \frac{1.6 \times 0.1 \times 25.6}{20} = \frac{4.096}{20} = 0.205\%$$

Table 3.11 reveals that the FFA content of the resulting biodiesel was 0.20%. This low FFA content is an indicator of an efficient process for biodiesel production and minimal saponification problems. Low FFA level is advantageous since it discourages unwanted side reactions and guarantees improved quality biodiesel and engine performance.

RESULTS AND DISCUSSIONS

In this chapter, experimental work results are discussed. The findings of catalyst manufacture and characterization, biodiesel production from WCO using the appropriate catalyst, WCOME (biodiesel) measurement using TLC and GC-MS techniques, and the impact of the catalyst on various operational parameters with regard to its reusability are all covered in the first section.

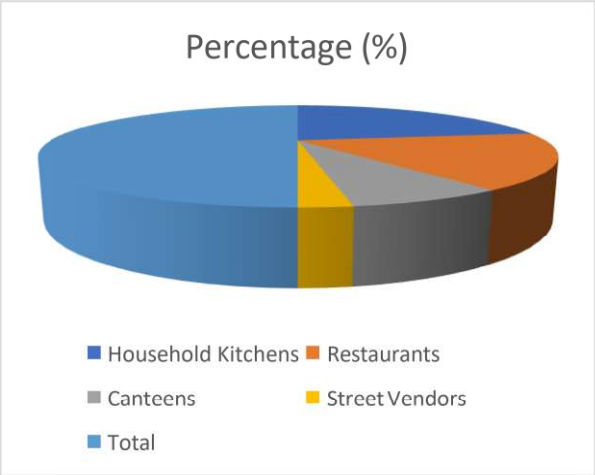
4.1. SAMPLE DATA INTERPRETATION

From a statistical standpoint, a sample size of 100 is considered appropriate for comparative and analytical studies involving simplified calculation.

Table 4.1 Origin of WCO Frequency Distribution

Source	Percentage (%)	Samples Collected frequency (n)
Household Kitchens	45%	45
Restaurants	35%	35
Canteens	15%	15
Street Vendors	5%	5
Total	**100%**	**100**

Figure:2.1.- Graphical Representation of Origin of used Cooking Oil



4.2. PRETREATMENT OF WCO BY ACID CATALYST RESULTS

Figure representing the kitchen source was found to the better quality of oil comparing from other sources to be used further for biodiesel production. Lower the acid value will provide better results for biodiesel production.

Figure: 2.2.- Acid Values of WCO of Different Sources

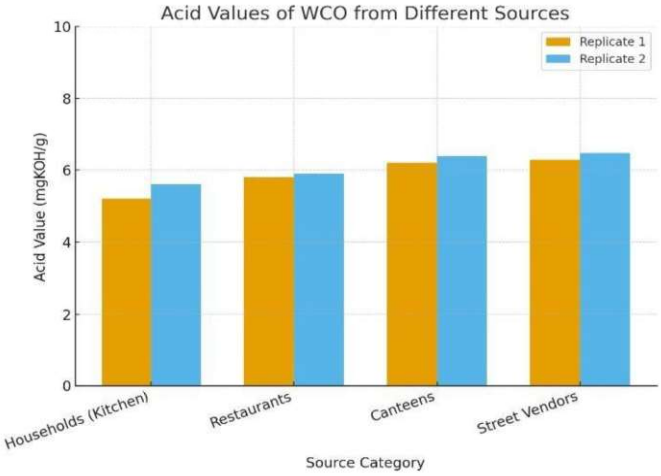
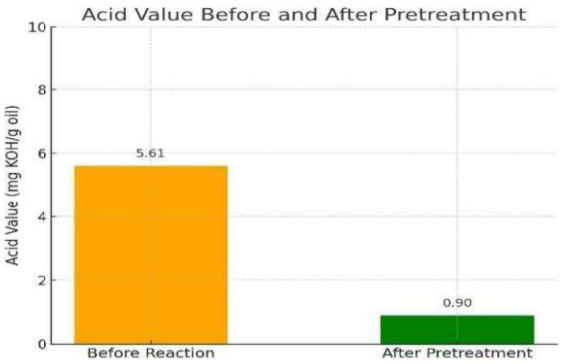


Figure: 2.3.- Comparison of Acid value before and after Pretreatment of WCO



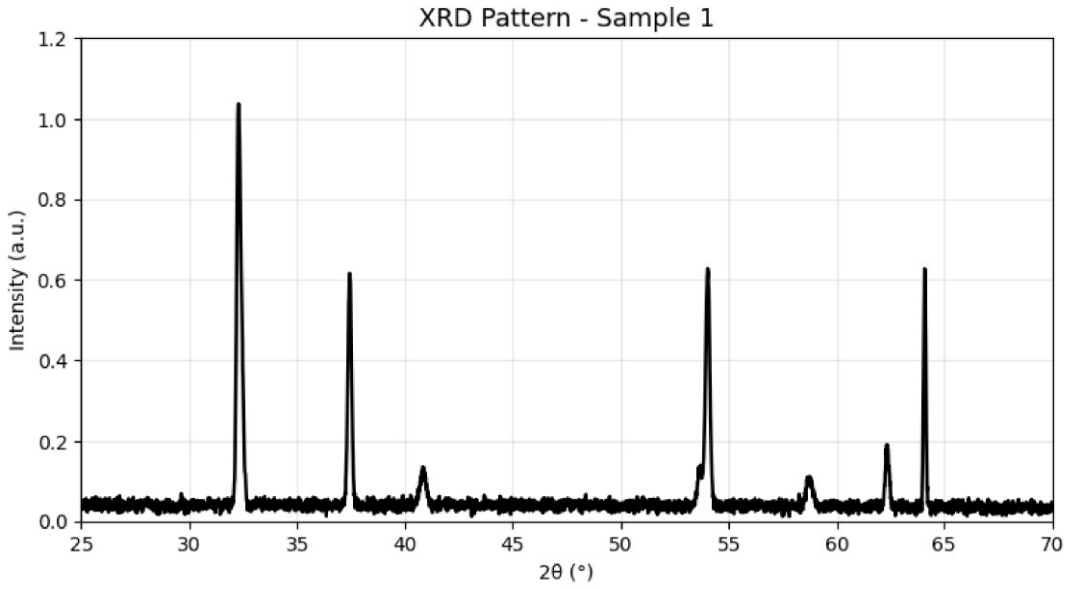
4.3. CATALYST CHARACTERIZATION

XRD was used to investigate the structural and elemental characteristics of Zn/CaO for the catalyst's characterization. It was used to study how zinc doping affected calcium oxide. XRD diffraction peaks ensured the existence of Zn/CaO and CaO in distinct phases. Diffraction patterns of both samples examined, one at 700°C and other prepared by wet impregnation with Zn-doped calcination at varying temperature ranges from 500 °C to 800°C. Sintering can cause when calcination occurs at higher temperature. This process leads to decrease in surface area of catalyst that ultimately reduce the active sites visibility. Zn doped introduced that prevent sintering using moderate calcinating temperature. This characterization method assisted in determining the structural changes, electron distribution, bond length and material properties of the Zn/CaO catalyst.

4.3.1 X-Ray Diffraction (XRD) Analysis

X-Ray Diffraction (XRD) measurements were conducted to study the impact of zinc doping on calcium oxide (CaO) structure. Every material has unique signature in the form of Kα radiation. The measurement employed Cu-Kα radiation (λ = 1.5406 Å) at a voltage of 40 kV and a current of 30 mA. The diffraction data was obtained to study the crystallinity and phase identification of pure CaO and Zn-doped CaO. The crystallite sizes were subsequently determined from Scherrer's equation using the diffraction peaks. This technique gave extensive information on how different concentrations of zinc affected the structural properties of CaO and its possible catalytic behaviour.

Table: 4.2.- Crystallite Size Calculation of CaO and Zn-Doped CaO Catalysts Based on XRD Analysis. Crystallite size for pure CaO catalyst.

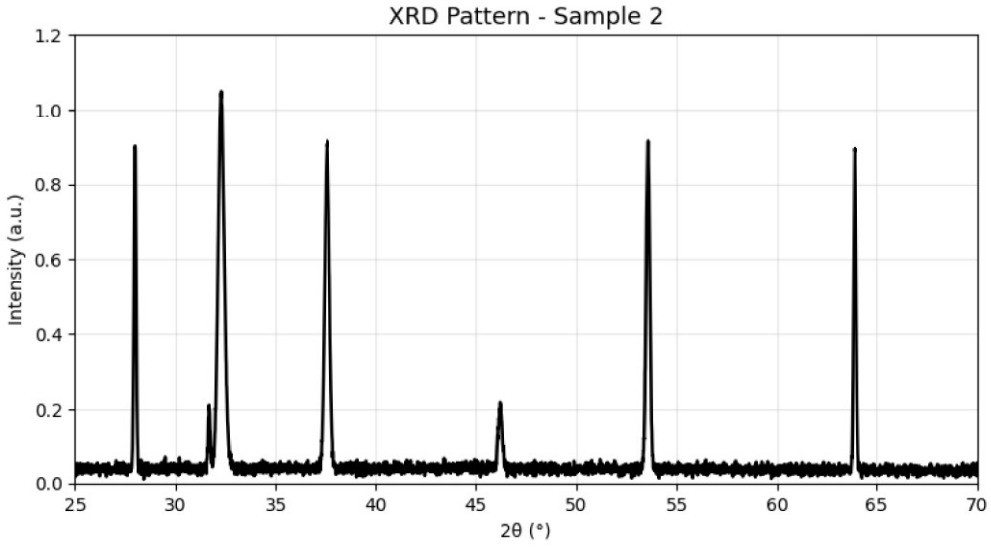


2θ (°)	FWHM (rad)	Crystallite Size D (nm)
28.00	0.0023	63.45
32.30	0.0064	22.10
37.57	0.0052	27.89
53.57	0.0037	34.95
63.89	0.0027	42.16

Crystallite size for 5%ZnCaO catalyst.

2θ (°)	FWHM (rad)	θ (°)	θ (rad)	Crystallite Size D (nm)
32.36	0.0045	16.18	0.2823	9.77
32.26	0.0028	16.13	0.2814	15.71
37.47	0.0035	18.735	0.3270	12.43
54.02	0.0040	27.01	0.4713	8.40
64.10	0.0022	32.05	0.5594	12.60

Table 4.2 shows the crystallite size calculations of CaO and Zn-doped CaO catalysts from XRD analysis. It is noted that the crystallite size increases stepwise with Zn doping up to 3%, with a maximum average size 34 nm and decrease size with an average 15nm for 5%-Zn/CaO. But at 7% Zn doping, the crystallite size again increases to 28.4 nm, which indicates that excess doping might introduce lattice strain, defect creation, or structural deformation in the catalyst.



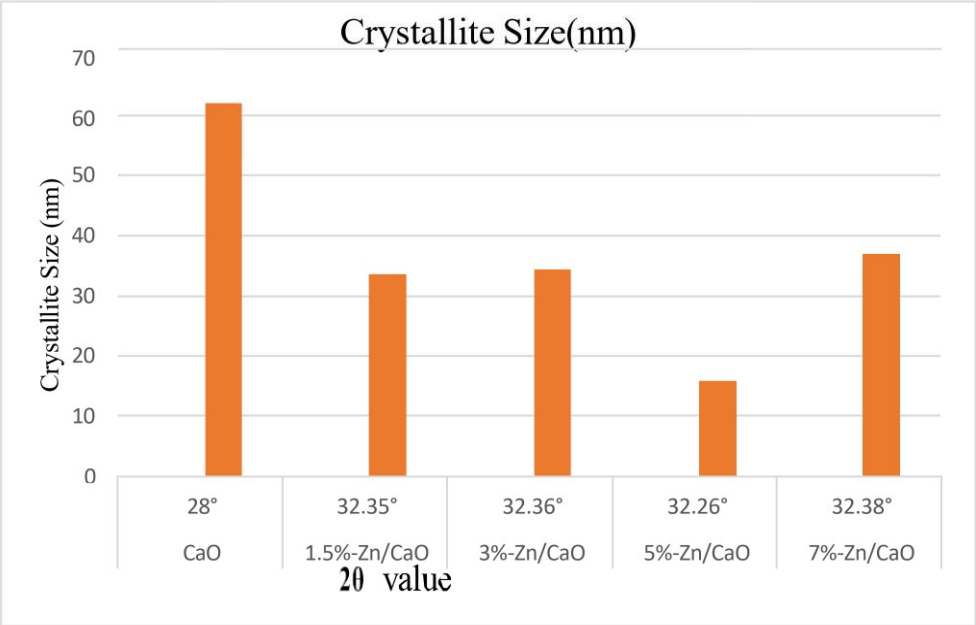


Figure: 2.4.- Variation of Crystallite Size with Zn Doping Percentage in CaO Catalysts

Sample	Main Peak (2θ)	FWHM (radians)	Crystallite Size (nm)
CaO	28°	0.0023	62.1
1.5%-Zn/CaO	32.35°	0.0043	33.6
3%-Zn/CaO	32.36°	0.0042	34.4
5%-Zn/CaO	32.26°	0.0051	15.71
7%-Zn/CaO	32.38°	0.0039	36.9

Table: 4.3.- Variation in Crystallite Size with Zn Doping Percentage in CaO Catalysts.

Figure 2.4 and table 4.3 Illustrates the change in crystallite size with Zn doping percentage. The graph indicates a consistent growth in crystallite size from 0% to 5% Zn doping, affirming that structural enhancement of crystallinity is triggered by controlled doping.

Characteristics indicate according to observation-

Broad peaks (large FWHM)	Small crystallites	High surface area
Sharp peaks (small FWHM)	Large crystallites	Low surface area
Peak height /intensity	Amount of phase	_----

It is illustrating all three parameters of Debye Scherrer equation. Depicting the crystalline size particle of CaO before and after Zn doped were found to be highest peaks 62.1 nm and average 15.7 nm at Zn loaded with 5wt%.

4.4. CHARACTERIZATION OF BIODIESEL

The progress of the reaction was tracked with the help of thin-layer chromatography (TLC), a method that is typically used for qualitative and quantitative analysis to separate organic molecules and measure their purity. The samples were collected on a regular basis, centrifuged to separate the catalyst, and tested with a hexane and ethyl acetate mobile phase mixture. The stationary phase was silica gel. By comparing the retention factor to a recognized reference standard, its existence as a by-product of biodiesel production was demonstrated. The solvent (mobile phase) was polar and the component sample was non polar so retention factor was found to be decreased. Gas Chromatography-Mass Spectrometry (GC-MS) spectroscopy was used to further determine the resulting fatty acid methyl ester (FAME). Using GC-MS spectroscopy, which provides information about the chemical composition of the synthesized methyl esters, distinct proton signals for the degree of reaction efficiency served as the basis for identification. By illustrating the effectiveness of the catalyst and reaction conditions used in the synthesis of biodiesel, this study helped to validate the structural changes in the transesterification process.

Transesterification procedure was catalysed by using zinc doped calcium oxide catalyst and physical and chemical parameters were observed on final biodiesel yield. The physical properties of biodiesel derived from waste cooking oil were evaluated, including kinematic viscosity, density, flash point, calorific value, ash content, and carbon residue. These properties were then compared with those of conventional diesel fuel based on ASTM standard protocols. The refined biodiesel exhibited a higher density (approximately 872 kg/m^3) compared to the typical diesel range of 830–860 kg/m^3. Its kinematic viscosity was also higher at 5.57 mm^2/s, while diesel generally falls within 1.9–4.1 mm^2/s. Due to this higher viscosity, biodiesel from recycled cooking oil is often blended with diesel to enhance performance. The flash point—defined as the temperature at which a fuel emits vapours that can ignite in air—was also notably higher for biodiesel, measured around 152 °C, compared to diesel's minimum standard flash point of 52 °C. A higher flash point indicates safer handling, storage, and transportation characteristics. The measurements of these and other relevant fuel properties are summarized in Table 3.

Table: 4.4.- Fuel properties for Zn doped CaO catalysed biodiesel compared to pure diesel on ATSM protocols.

PROPERTY	Typical Range of diesel ASTM std.	BIODIESEL
Density @31°C	830–860	872kg/m³
Kinematic Viscosity @40°C	1.9–4.1 mm²/s	5.5 cSt
Flash Point	≥ 52 °C	152 °C
Cloud Point	-15 to +5 °C (varies)	5
Pour Point	-35 to 0 °C (varies)	2
Carbon Residue	≤ 0.35% (by mass)	0.04%
Ash Content	≤ 0.01% (by mass)	0.02%
Fire Point	~65–96 °C	164
Calorific value	~45,000–46,000 kJ/kg	38 MJ/kg

4.4.1 Thin layer Chromatography Analysis

Thin Layer Chromatography (TLC) experiment for biodiesel is a simple and effective method to analyze the conversion of triglycerides (WCO) into biodiesel (fatty acid methyl esters, FAMEs) during the transesterification process that confirm the presence of FAMEs, triglycerides, diglycerides, and monoglycerides.

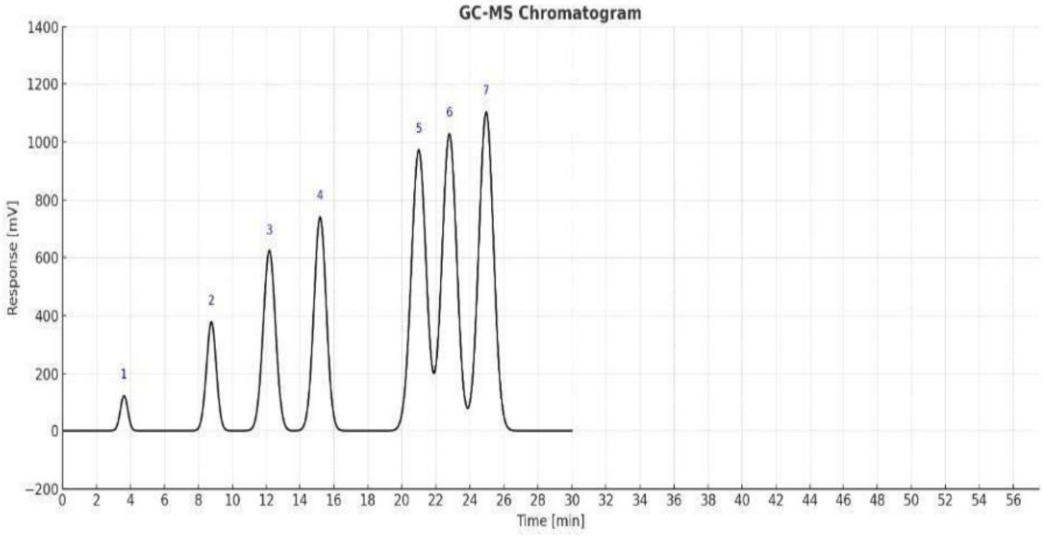
Table: 4.5.- TLC Observation and Calculation for Retention Factor (Rf)

Samples loaded on to silica plate of TLC	Retention factor
1. Waste Cooking Oil	3.3/6 = 0.55
2. WCO biodiesel	4.3/6 = 0.71
3. Methyl oleate (as a reference)	0.65 -0.80

4.4.2 Fatty Acid Methyl Ester (FAME) result analysis using GC-MS

To accurately determine the composition of biodiesel, Gas Chromatography–Mass Spectrometry (GC-MS) was used to analyze the fatty acid methyl esters (FAMEs) present in the trans esterified product. GC-MS is a widely accepted technique for the qualitative and quantitative assessment of individual fatty acids, offering high sensitivity and precise identification of molecular structures.

Figure: 2.5.- Chromatogram was obtained from GC-MS for FAME content results.



The relative composition (%) of each methyl ester was determined by integrating the peak areas and normalizing them against the total peak area. The methyl esters found in waste cooking Oil-based biodiesel accounting for approximately 82.4 % of the total FAME content.

Table: 4.6.- GC-MS Integration results

Compound Name	Height (mV)	Retention time	Area %	wt. %
Methyl heptanoate (C7:0)	123.17	3.625	2.48%	1.28%
Methyl tetradecanoate (C14:0)	378.13	8.755	7.60%	6.59%
Methyl pentadecanoate (C15:0)	623.72	12.162	12.54%	11.50%
Methyl hexadecanoate (C16:0)	742.31	15.202	14.93%	14.44%
Methyl linoleate (C18:2)	1028.38	22.448	20.69%	21.77%
Methyl oleate (C18:1)	1103.25	24.963	22.19%	23.52%
Methyl stearate (C18:0)	973.21	21.529	19.57%	20.90%
Total	**5230.23**		**100%**	**100%**

Table 4.6 shows the major FAME compounds found in the biodiesel sample using GC-MS analysis. The major components identified were Methyl Oleate (23.52%), Methyl hexadecanoate (14.44%), Methyl Stearate (20.90%), and Methyl Linoleate (21.77%). High unsaturated methyl esters such as Methyl Oleate reflect good quality biodiesel with positive combustion and flow characteristics. The composition of FAMEs verifies the effective conversion of waste cooking oil into biodiesel with a balanced proportion of saturated and unsaturated esters

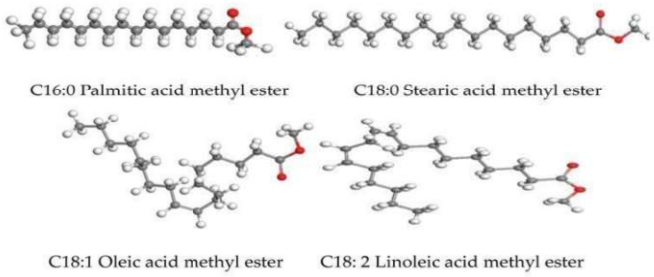


Figure: 2.6.- GC-MS chromatogram showing the FAME profile of biodiesel derived from waste cooking oil.

GC-MS characterization confirms the successful transesterification of waste cooking oil into biodiesel, with a well-defined FAME profile dominated by long-chain unsaturated and saturated fatty acid esters. The method provides a reliable, precise, and reproducible means to evaluate biodiesel quality in accordance with ASTM D6584 standards.

4.5. OPTIMIZATION OF REACTION PARAMETERS

4.5.1 Effect of Methanol to Oil Molar Ratio

Biodiesel production cost and the success of Transesterification reaction are very sensitive to the molar ratio of methanol to oil. According to stoichiometry, three moles of methanol are required for every mole of oil in order to trans esterify vegetable oil (3:1) an excessive amount of methanol tilts the balance in Favor of methyl ester yield because excessive alcohol both accelerates the rate of transesterification reaction and remove product molecules form the surface of the catalyst thereby regenerate the catalytic site. Because manufacturing biodiesel with too much methanol might be expensive, finding the optimal molar ratio was critical for keeping process cost down. When heterogenous catalyst were used to make biodiesel, the most common molar ratio was 3:1, 6:1, 9:1 & 12:1 at that point. The most effective molar ratios were 9:1,6:1 and 12:1 molar ratio resulted in a biodiesel yield of 82.3%. At molar ratio more than 12:1 the reaction was not fully completed because the glycerol was difficult to separate and some of the glycerol remain in biodiesel, reducing the apparent biodiesel production.

The impact of molar ratio on the transesterification reaction of waste cooking oil WCO catalyzed by 5% Zn-dopped CaO-700 is depicted in the figure 4.3 four molar ratios (3:1, 6:1, 9:1,12:1 and 15:1) are considered in the study to ascertain how the effect the reaction. To track the process development data points are collected at various interval of 90, 180, 300, 420 minutes. The finding provides information about the effects of several molar ratios on the 5% Zn-dopped CaO-700 catalyzed transesterification of obtained biodiesel waste cooking oil (WCO).

Table: 4.7.- Effect of Methanol to Oil ratio on FAME yield%

Sample	Methanol: Oil Ratio	FAME Yield (%)
5% Zn-CaO	03:01	65
5% Zn-CaO	06:01	75
5% Zn-CaO	09:01	79
5% Zn-CaO	12:01	82.3
5% Zn-CaO	15:01	76

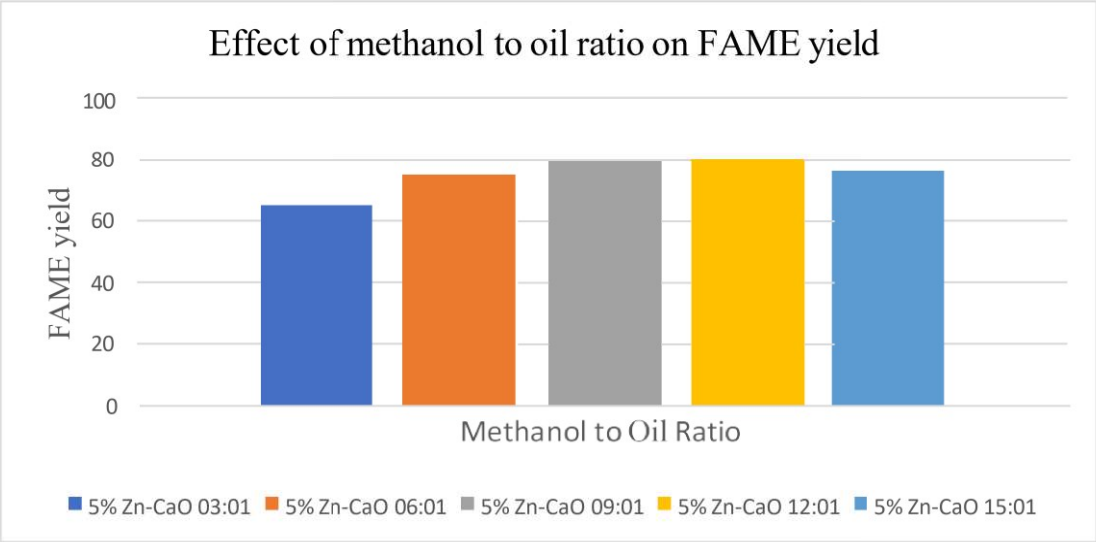


Figure: 2.7.- Effect of Methanol to Oil ratio on FAME yield%

4.6. EFFICIENCY MEASUREMENTS OF CATALYST

This section analyzes the catalytic activity of Zn/CaO catalysts by studying the effect of different parameters like zinc doping, calcination temperature, catalyst loading, reaction time, and reusability of the catalyst on the production of biodiesel from waste cooking oil. Catalytic activity was quantified in terms of biodiesel yield and reaction time under optimized conditions. Results indicated increased biodiesel yield and minimized reaction time upon doping zinc onto CaO, with 5-Zn/CaO-700 exhibiting the best performance. In the same

manner, calcination temperature of 700°C gave the best yield, whereas 5 wt% catalyst loading was optimum. Reaction time was stabilized around 300 minutes to have maximum yield, and the catalyst had satisfactory reusability up to three cycles. Nevertheless, beyond these ideal conditions, additional increments in doping, temperature, or number of cycles produced lower yields, which suggests the necessity for precise catalyst conditions to achieve effective biodiesel production.

4.6.1 Effect of Doping on Catalyst

The influence of zinc doping on calcium oxide (CaO) was assessed by synthesizing catalysts with various doping percentages of Zn (1.5%, 3%, 5%, and 7%) over CaO. Catalysts were synthesized under uniform conditions for the transesterification of waste cooking oil, utilizing a methanol-to-oil molar ratio of 12:1, a reaction temperature of 60–65°C, and a constant catalyst loading of 5 wt.%. The reaction was conducted for various durations, and the yield of biodiesel was assessed. The aim was to identify how different concentrations of Zn affected the capacity of the catalyst in converting waste cooking oil into biodiesel, and to optimize reaction duration and yield efficiency.

Procedure:

The influence of zinc doping on calcium oxide (CaO) was assessed by synthesizing various percentages of doping of Zn (1.5%, 3%, 5%, and 7%) over CaO. The catalysts were prepared under the same conditions for the transesterification of waste cooking oil, with a methanol to oil molar ratio of 12:1 and the reaction temperature being between 60–65°C. The catalyst loading was kept constant at 5 wt.%(5.26gm). The reaction was performed for various times, and the biodiesel yield was quantified. Each sample was prepared with extreme care, and the reaction time and biodiesel yield for each catalyst composition were noted. The objective was to determine how Zn concentrations varied affected the catalyst's efficiency in the conversion of waste cooking oil into biodiesel in terms of reaction time and yield efficiency.

Observation:

The doping of zinc on calcium oxide highly improved the catalytic activity of the CaO catalyst in the waste cooking oil transesterification, as indicated in Table 4.8. Increasing the percentage of zinc doping to 5% enhanced the biodiesel yield and decreased the reaction time significantly. The highest yield of fatty acid methyl ester (FAME) of 96.2% was obtained by the 5 -Zn/CaO-700 catalyst within only 5 hours. Yet, upon increasing the doping level to 7%, biodiesel yield declined to 89.2%, implying that a surplus of zinc will compromise the structural integrity of

the catalyst or fill up active sites, lessening its activity. This indicates that an optimal compromise between increased efficiency of conversion and shorter reaction time is obtained from a 5% Zn doping level.

Table: 4.8.- Comparison of Biodiesel Yield and Reaction Time for Different Zn Doping Levels on CaO Catalyst

Catalyst	Doping (%)	FAME Yield (%)	Reaction Time (h)
CaO	0	99.7	5.0
Zn/CaO-700	1.5	93.7	5.0
Zn/CaO-700	3.0	94.8	5.0
Zn/CaO-700	5.0	96.2	5.0
Zn/CaO-700	7.0	89.2	5.0

Figure:2.8.- Effect of different doping catalyst on FAME yield at reaction time (5 hr)

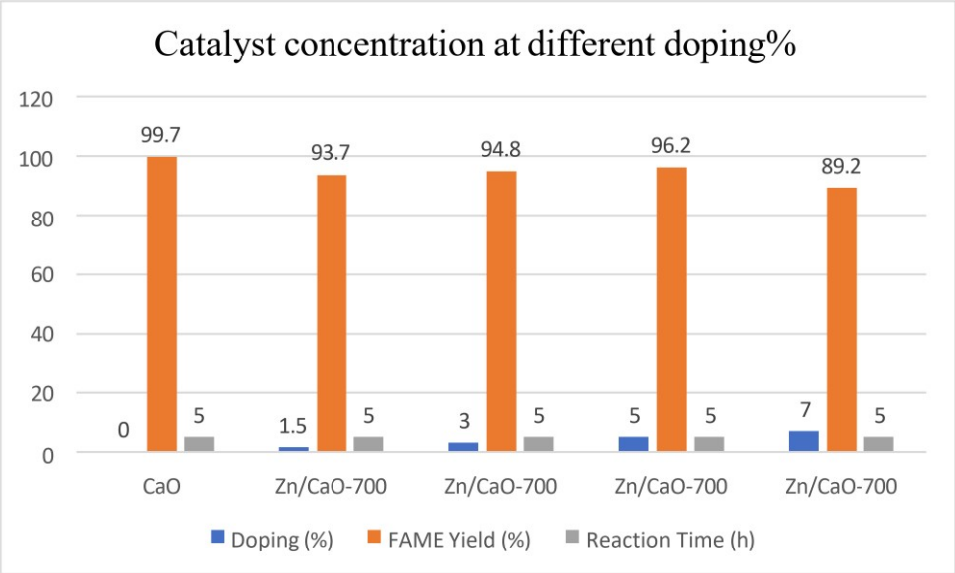


Table: 4.9.- Effect of different doping catalyst on FAME yield at reaction time (2.5 hr) at methanol to oil molar ratio 9:1.

Catalyst	Zn Doping (%)	FAME Yield (%) at 2.5 h
CaO	0	65.2%
1.5% Zn/CaO	1.5	70.5%
3.0% Zn/CaO	3.0	72.4%
5.0% Zn/CaO	5.0	75.1%
7.0% Zn/CaO	7.0	71.2%

Zinc doping on CaO greatly improved the catalytic activity in waste cooking oil transesterification. In Table 4.9, Zn doping increased up to 5% gave better biodiesel yield and decreased reaction time considerably, with 5-Zn/CaO-700 providing the best FAME yield (96.2%) in5 hours. In table 4.7 Yet a doping 1.5% to 7% at methanol to molar ratio 9:1 with reaction time lower (2.5 hours) resulted in loss of yield with average 70.2%, suggesting that too much zinc in less time does not convert WCO effectively in to biodiesel that might adversely impacted on catalyst structure or active sites. Therefore, an optimal 5% Zn doping level achieves the optimal compromise between efficiency and reaction rate.

4.6.2 Effect of Calcination Temperature on Catalyst

The influence of the calcination temperature on the catalytic activity of the Zn/CaO catalyst was measured by calcining the catalysts at varying temperatures (500°C, 600°C, 700°C, and 800°C). The catalyst precursors were heated under the furnace to the target temperatures in a controlled atmosphere. The calcined catalysts were utilized for the transesterification of waste cooking oil to biodiesel with the reaction under consistent conditions. The goal was to find out the effect of the calcination temperature on catalytic activity and to learn the most appropriate temperature for ultimate efficiency in the production of biodiesel.

Procedure:

The influence of calcination temperature on the catalytic activity of the Zn/CaO catalyst was assessed by calcining the catalysts at different temperatures, namely 500°C, 600°C, 700°C, and 800°C. Calcination was carried out in a furnace, where the catalyst precursors were subjected to the target temperatures under controlled conditions. The calcined catalysts were then applied to the transesterification reaction of waste cooking oil to biodiesel. The biodiesel yield was also quantified at every temperature, and the reaction was performed in the same conditions to make certain that differences observed in yield were caused by differences in calcination temperature. The process facilitated determination of the ideal calcination temperature that would be able to increase catalytic efficiency.

Observation:

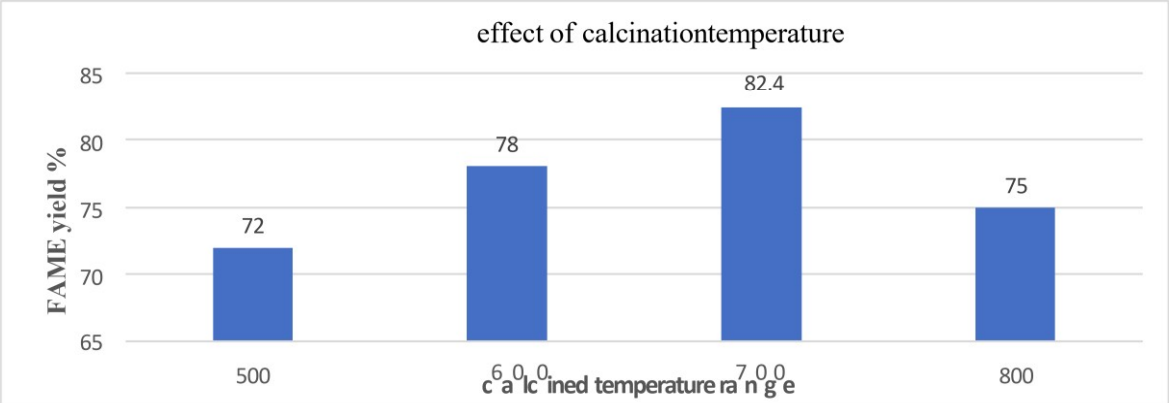
As indicated in Table 4.10, the calcination temperature had a notable effect on the catalytic activity of the Zn/CaO catalyst. Yield of biodiesel improved with increasing calcination temperatures up to 700°C, with the best yield of 82.4% being realized at this temperature. This confirms that the calcination process enhanced the structure and activity of the catalyst up to 700°C. However, when the calcination temperature was raised from 700°C to 800°C, a very

small reduction in the yield was noticed, lowering to 75%. This reduction would be attributed to sintering, a condition that arises at elevated temperatures and results in the loss of active surface area, hence lowering the efficiency of the catalyst. Thus, 700°C was chosen to be the best calcination temperature at which maximum catalytic activity and yield of biodiesel was noticed.

Table: 4.10.- Effect of Calcination Temperature on Biodiesel Yield Using Zn/CaO Catalyst

Calcination Temperature (°C)	FAME Yield (%)
500	72.0
600	78.0
700	82.4
800	75.0

Figure: 2.9.- Effect of Calcination Temperature on Biodiesel Yield Using Zn/CaO Catalyst.



Calcination temperature played an important role in catalytic activity of Zn/CaO. As can be seen from Table 4.10, biodiesel yield improved with increasing calcination temperatures up to 700°C and had a maximum yield of 82.4%. At temperatures higher than 700°C, there was a drop-in yield (75% at 800°C) attributed to catalyst sintering and loss of active surface area. The optimum calcination temperature was thus determined to be 700°C.

4.6.3 Effect of Catalyst Loading

The influence of catalyst loading on the yield of biodiesel was explored by changing the concentration of the catalyst between 1.5 wt% to 7 wt% while maintaining other reaction conditions unchanged, including the methanol-to-oil molar ratio (12:1), temperature (60–

65°C), and reaction time. Catalyst loading was achieved through precise weighing of various quantities of Zn/CaO catalyst and its addition to the reaction mixture. Once the transesterification is complete, the yield of biodiesel was recorded. The aim of the experiment was to determine the ideal quantity of catalyst that would yield the highest biodiesel production, while maintaining the process efficiency without causing problems like mass transfer limitations.

Procedure:

The influence of the loading of a catalyst on the yield of biodiesel was evaluated by changing the catalyst concentration within the range from 1.5 wt% to 7 wt%, without any variation of other reaction parameters. The constant reaction conditions in the form of methanol-to-oil ratio (12:1), reaction temperature (60–65°C), and time were used throughout each experiment. Catalyst loading was achieved by accurate weighing of diverse quantities of the Zn/CaO catalyst, followed by charging into the reaction mixture. The yield of biodiesel was then quantified following the process of transesterification. Through a change in catalyst loading, the experiment sought to identify the best quantity of catalyst that would produce maximum yield of biodiesel without bringing about inefficiencies such as high mass transfer limitations.

Observation:

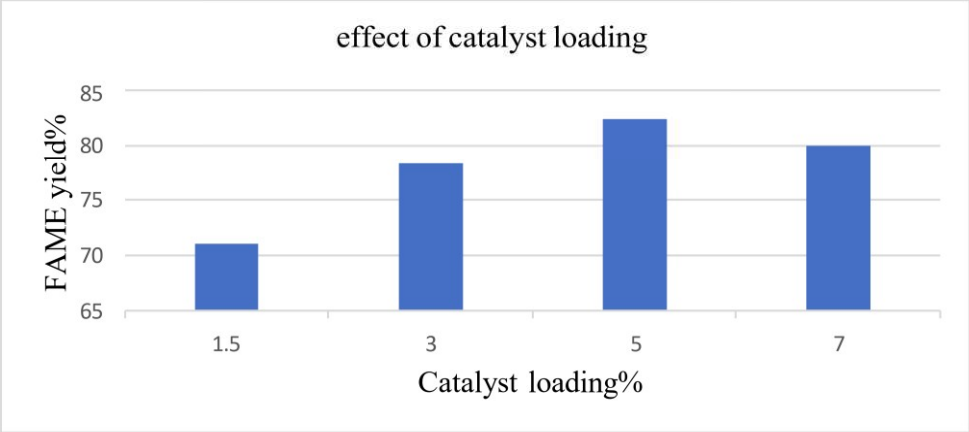
As indicated in Table 4.11, the catalyst loading played a critical role in biodiesel yield. A rise in catalyst loading from 1.5 wt% to 5 wt% resulted in a steady increase in biodiesel production, with the highest yield of 82.4% at 5 wt%. This indicates that increased catalyst loading enhances the efficiency of the transesterification process, allowing for improved conversion of the oil to biodiesel. At 7 wt% catalyst loading, the biodiesel yield was reduced to 80%. This drop is due to mass transfer limitations, as the increased concentration of the catalyst raised the viscosity of the reaction mixture, reducing the capacity of the reactants to diffuse appropriately. Therefore, the best catalyst loading was found to be 5 wt%, as it struck an optimal balance between conversion and efficiency.

Table: 4.11.- Effect of Catalyst Loading on Biodiesel Yield Using Zn/CaO Catalyst

Catalyst Loading (wt.%)	FAME Yield (%)
1.5	71.0
3.0	78.30

5.0	82.4
7.0	80.0

Figure: 2.10.- Effect of Catalyst Loading on Biodiesel Yield Using Zn/CaO Catalyst



Loading of catalyst greatly impacted the yield of biodiesel as reflected in Table 4.11. The yield was increased by raising the loading from 1.5 wt% to 5 wt%, with 5 wt% yielding the highest biodiesel production (82.4%). If the loading was further increased to 7 wt%, however, yield decreased (80%) because of mass transfer restrictions and rising mixture viscosity, which makes 5 wt% the best catalyst loading for effective transesterification.

4.6.4 Effect of Reaction Time

The impact of reaction time on the transesterification reaction was investigated by following the reaction over varying time periods 90, 180, 300, and 420 minutes. The yield of biodiesel was recorded at every interval, and samples were withdrawn to monitor the progress of the reaction. The reaction was carried out under identical conditions such as a methanol-to-oil molar ratio of 12:1, a catalyst loading of 5 wt%, and a temperature range of 60 –65°C. The research sought to establish the best time taken by the reaction to achieve equilibrium and the time taken to attain the maximum biodiesel yield effectively.

Procedure:

The transesterification reaction was tracked for different time periods—90 minutes, 180 minutes, 300 minutes, and 420 minutes—to find out the time needed for the reaction to achieve equilibrium. The yield of biodiesel was quantified at every time interval, and the progress of the reaction was monitored by withdrawing samples of the reaction mixture at intervals. The reaction conditions like the methanol-to-oil molar ratio (12:1), catalyst loading (5 wt%), and

temperature (60–65°C) were maintained constant during the experiment. By monitoring the conversion of waste cooking oil (WCO) to biodiesel at different time intervals, the research intended to determine the optimum reaction time required to obtain maximum biodiesel yield and determine the time taken to attain equilibrium in the process of transesterification

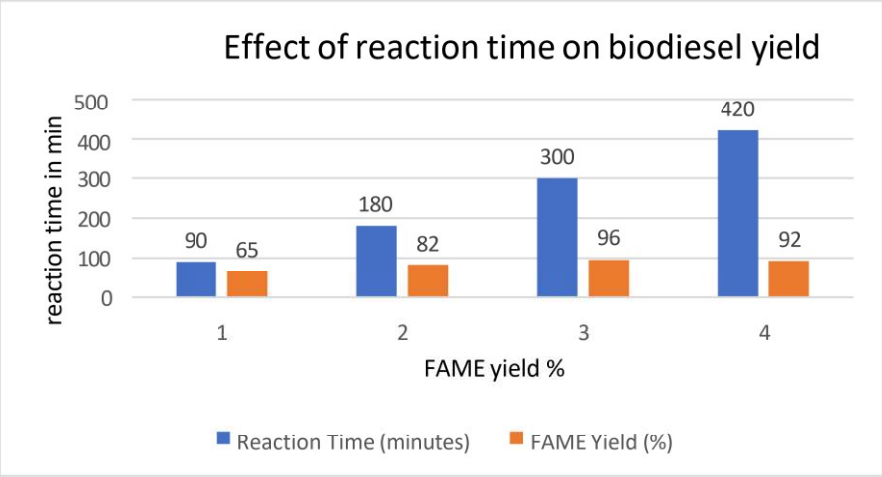
Observation:

As indicated from Table 4.12, the yield of biodiesel rose continuously with the reaction time. The conversion was 65% at 90 minutes, 82% at 180 minutes, 96% at 300 minutes, and 92% at 420 minutes, showing that the reaction was close to completion. Beyond 90 minutes, prolonging the reaction time to 180 minutes only slightly increased the yield (82%), which indicated that the reaction had almost reached equilibrium at 180–300 minutes. Thus, a reaction time of about 300 minutes was found to be ideal for maximum biodiesel yield since prolonging the time further offered insignificant advantages and would only consume unnecessary energy.

Table: 4.12.- Effect of Reaction Time on Biodiesel Yield during Transesterification of WCO

Reaction Time (minutes)	FAME Yield (%)
90	65
180	82
300	96
420	92

Figure: 2.11 Showing effect of reaction time on Biodiesel yield during transesterification reaction of WCO.



As shown in Table 4.12, yield of biodiesel rose constantly with reaction time, achieving a level of about 65% conversion at 90 minutes and 82% at 180 minutes. Exceeding 300 minutes, a further prolongation of the reaction time up to 400 minutes resulted decrease in a (96%), reaction proving that by 300 minutes, the reaction was practically at the stage of equilibrium. Thus, an optimal duration of reaction around 300 minutes is adequate to produce the highest biodiesel content without wastage of energy.

4.6.5 Reusability of Catalyst

The reusability of the 5-Zn/CaO-700 catalyst was also tested by carrying out successive transesterification reactions using the same catalyst repeated for numerous cycles. Following each reaction, the catalyst was recovered, washed to eliminate any of its leftover biodiesel and impurities, and finally dried for repeated use under the same reaction conditions. This was repeated for a number of cycles to determine the durability and performance retention of the catalyst. The objective was to find out how the catalyst's activity changed with reuse and whether it could retain its catalytic efficiency over time.

Procedure:

The reusability of the 5-Zn/CaO-700 catalyst was investigated through successive transesterification reaction using the catalyst for repeated cycles. After each reaction, the catalyst was treated carefully to remove it from the reaction mixture through filtration, rinsed well in order to purify the residual biodiesel and impurities, and then dried. The dehydrated catalyst was recycled in the next reaction under the same conditions, such as the same methanol-to-oil molar ratio (12:1), reaction temperature (60–65°C), and catalyst loading (5 wt%). This was done in multiple cycles to test the durability and retention of the catalyst's performance. The yield of biodiesel in each cycle was determined and compared to see how the performance of the catalyst varied with recycling.

Observation:

As indicated by Table 4.13, the 5-Zn/CaO-700 catalyst had outstanding catalytic activity for the initial three cycles, producing biodiesel yields of 96.7%, 92.8%, and 89.5%, respectively. This indicates that the catalyst was still efficient for multiple uses with minimal drop in yield between the first and second cycles. However, a significant reduction in yield to 85.0% was noted in the fourth cycle after the third cycle, reflecting some level of catalyst deactivation. This reduction in yield is thought to result from loss of active sites or changes in structure of the catalyst following repeated use, which restricted its performance. In spite of this, the

catalyst was highly recyclable for three cycles and showed promise for sustainable biodiesel production with very little loss of efficiency.

Table: 4.13.- Reusability of 5-Zn/CaO-700 Catalyst in Successive Transesterification Cycles

Cycle Number	FAME Yield (%)
1st Cycle	96.7
2nd Cycle	92.8
3rd Cycle	89.5
4th Cycle	85.0

Reusability analysis presented in Table 4.13 indicates that the 5-Zn/CaO-700 catalyst remained in top form for a maximum of three cycles with biodiesel yields of 96.7%, 92.8%, and 89.5%, respectively. However, there was a sharp decline in yield to 85.0% during the fourth cycle due to probable deactivation of the catalyst and loss of active sites. Therefore, the catalyst can be reused up to three times with negligible loss of efficiency. The cost of producing biodiesel determines how well the technique works. Reusable catalysts may reduce the cost of producing biodiesel to a certain degree. Following transesterification, the 5Zn/Cao-700 catalyst was recovered, filtered, cleaned with hexane, and then calcined once more at 700°C to determine its reusability. Using the same regeneration and experimental procedures, the regenerated catalyst was used for four consecutive catalytic cycles. Figure 4.9 shows that there was a minor decline in catalytic activity in the fourth cycle, but no discernible loss of activity during the first three runs. The slow decline in catalytic activity may be caused by partial leaching of the active species from the catalyst or by the absorbed organic molecules blocking the active sites.

Figure 4.10 shows the reusability test of the 5Zn/CaO-700 catalyst, analyzing its performance over several cycles. The test gives information on the stability and effectiveness of the catalyst under repeated use, indicating its potential for long-term use in catalytic processes. The test is crucial in ascertaining the durability and efficacy of the catalyst in delivering consistent performance over repeated runs.

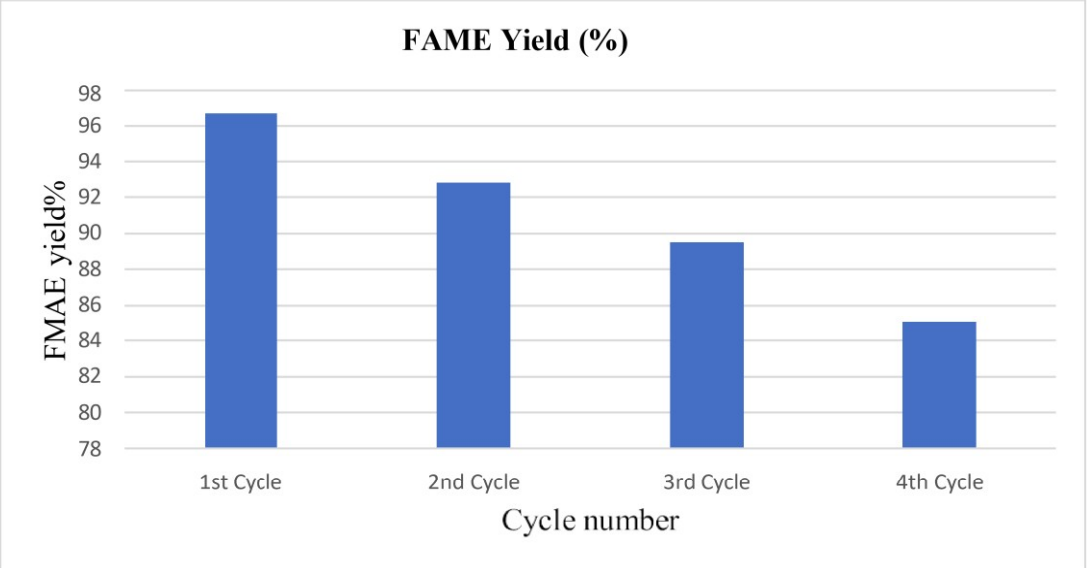


Figure: 2.12.- Graphical representation of Reusability of Catalyst.

With a consistent FAME output of 96.7% throughout the first two cycles drop to 92.8% in the third, the 5Zn/CaO-700 catalyst's reusability experiment demonstrates its high initial activity. However, the sharp decline to 85% in the fourth cycle indicates a notable drop-in catalytic activity, suggesting that the catalyst was likely deactivated by surface fouling, leaching of active sites, or structural alteration. The findings emphasize that though the catalyst displays encouraging stability during the early cycles, its poor performance in subsequent cycles indicates a necessity for regeneration protocols or optimization to improve long-term reusability in catalytic processes.

4.7. BIODIESEL'S PROPERTIES AND SIGNIFICANCE

The type of feedstock and its fatty acid composition determine the chemical and physical properties of the fuel. The physical and chemical properties of biodiesel produced from spent cooking oil were studied at Jhansi. The outcomes are listed in Table 4.8. According to EN14214 and ASTM D6751 standards, the sample was acceptable. This section explains the basics of biodiesel and why they're important. The flow resistance of a liquid can be directly measured by its kinematic viscosity. For that reason, it is an essential quality for determining the fuel economy of biodiesel. Due to issues with fuel atomization, tube obstruction, and possible deposit deposition in the engine, the high viscosity of the liquid fuel would be detrimental to its quality. These issues lead to incomplete combustion and severe fouling.

Because viscosity is inversely proportional to temperature, a fuel's suitability for use in cold climates is compromised when the temperature drops below a certain point. Waste methyl

ester from cooking had a kinetic viscosity of 5.57 centistokes at 40°C, which was used in this experiment. Between 1.9 to 6.0 cSt is the suggested range by ASTM, which this figure falls under. The cooking residue methyl ester was found to have a density of 876.2 kg/m3. The density of fuel is important because it shows the specific energy per mass and the ignition quality, or the amount of time it takes for diesel fuel to get from injection to combustion. Biodiesel's higher density compared to diesel oil fuel is directly responsible for the increased fuel consumption and, ultimately, NOx emissions. The biodiesel's density was determined by use of the ISI448 P: 32 test procedures.

The standard temperature for density tests is 31°C, according to these criteria. Biodiesel fuel has a higher flash point than diesel oil fuel made from petroleum, which is an additional advantage. The flash point is a measure of how flammable gasoline is; a higher flash point indicates that the gasoline is safer to store and handle. The project's biodiesel has a flash point of 152°C, which is greater than diesel oil's 52-96°C. Conversely, diesel engine efficiency is negatively impacted by substances with a high flash point because of their poor volatility properties. How biodiesel performs in cold environments or when exposed to low temperatures is an important quality aspect. This is due to the fact that when fuel partially or completel y solidifies, it can clog the fuel lines and filters, which in turn causes fuel starvation, problems starting and driving, and engine damage from inadequate lubrication.

When working with low-temperature fuels, the gasoline's cloud point and pour point are crucial. The cloud point is the temperature at which, in a controlled environment, wax crystals initially form when fuel is cooled during a standard test. At the pour point, the fuel will solidify due to the presence of enough wax in the solution, marking the lowest temperature at which it can flow. Biodiesel typically has higher cloud and pours points than diesel oil fuel. The acid value is the concentration of potassium hydroxide required to dissolve one gram of FAME.

The fuel supply system of an engine is quite vulnerable to severe corrosion from increased acidity. The acid value is determined using the ASTM D664 standard. In this study, the concentration of KOH was 0.44 mg/g of material. In addition to determining the level of unsaturation, the iodine number shows how many double bonds are present in biodiesel. This property has an impact on the stability of glycerides during polymerization and oxidation.

The amount of potassium hydroxide (KOH) required to completely neutralize the free fatty acids and saponify one gram of an ester, oil, or fat is the saponification value. It is possible to approximate the average molecular weight of oil or fat using the saponification value.

Another thing that the saponification value shows is how long the carbon chain of the acid is in that particular fat or oil. The number of times an oil or fat has been saponified is inversely proportional to the percentage of short-chain acids found in its glycerides. The saponification value of the methyl ester in discarded cooking oil was determined using the ASTM D5558 procedure. The engine ran more smoothly and quietly with the higher cetane number (54.5) than with diesel oil. Although the biodiesel sample's 10% oxygen concentration contributes to its beneficial emissions, its calorific value (38 MJ/kg) is slightly lower than that of petroleum-diesel. Biodiesel produced from WCO offers acceptable values when compared to diesel oil fuel since it nearly entirely meets all of the properties of conventional diesel oil fuel, as stated in ASTM D6751 and EN 14214 regulations.

4.8. MARKET PRICE VALUE OF BIODIESEL (B100)

Using 20 g of waste cooking oil (WCO) priced at ₹25-30 per litre (≈₹0.028/g), the feedstock cost amounts to about ₹0.56. For transesterification, 11mL of methanol was used, with market prices ranging between ₹60 per litre (₹0.06/mL), resulting in a cost of ₹1.50. The catalyst (CaO and Zn) applied at 5 wt% of oil (1 g), contributes an additional ₹0.15 based on the market price of ₹150 per kg. Altogether, the raw material cost per batch (20 g oil → 17 g biodiesel at 82.7% yield) falls in the with ₹2.21. When normalized to the biodiesel obtained, this corresponds to ~₹0.13 per gram, which scales to approximately ₹115-120 per litre of biodiesel. These values represent laboratory-scale production costs without methanol recovery or glycerol credit. In industrial practice, methanol recycling, catalyst optimization, and by-product utilization reduce the effective cost significantly, often lowering the price to around ₹105 per litre on-road.

4.9. WHY TO RELIANCE ON BIODIESEL

1. Biodiesel in its pure, unblended form (B100) is much less harmful to the environment than petroleum diesel if spilled or released. It is also safer to handle because it is less flammable; biodiesel has a flashpoint above 130 °C, compared to roughly 52 °C for petroleum diesel. This higher flashpoint makes biodiesel safer for storage, transport, and handling. Additionally, using biodiesel and other advanced alternative fuels contributes to energy security by providing resilient, energy-efficient transportation options that can better withstand natural disasters and fuel supply disruptions.

2. In countries like United States and Dubai biodiesel is produced domestically and can be used in conventional diesel engines as either a direct substitute for, or a blend with, petroleum diesel. WCO-based biodiesel, demonstrates a strong positive energy balance. This efficient energy

return, along with reductions in nitrogen oxide (NOx) emissions, allows biodiesel to perform comparably to petroleum diesel in terms of regulated air pollutant emissions.

3. Biodiesel also lowers life cycle greenhouse gas emissions. The carbon dioxide released when biodiesel is burned is largely offset by the carbon dioxide absorbed during the cultivation of feedstocks used to make the fuel. A life cycle assessment by Argonne National Laboratory found that using B100 can cut carbon dioxide emissions by up to 74% compared with petroleum diesel.

4. From a practical standpoint, biodiesel is one of the easiest alternative fuels to adopt. It requires no modifications to existing diesel engines, meaning nearly all diesel-powered equipment can operate on biodiesel without issue. It is also environmentally friendly, producing lower emissions and contributing to improved air quality both outdoors and in workplaces.

Biodiesel production supports American farmers since it is often made from domestic WCO, and its use helps reduce dependence on imported oil, thereby enhancing national energy security.

5. Performance-wise, biodiesel blends closely match traditional diesel fuels. For instance, B20 biodiesel has less than a 2% difference in energy content compared to petroleum diesel, with most users reporting little to no noticeable impact on fuel economy. Biodiesel also provides excellent lubricity, which helps extend the service life of fuel injection systems.

SUMMARY, CONCLUSION AND RECOMMENDATION

5.1. SUMMARY

Transesterification is an eco-friendly waste management technique that creates a renewable substitute for fossil fuels by turning used cooking oil into biodiesel. Improper disposal of used cooking oil can contaminate the environment. However, it can be made into a useful product that reduces environmental risks and the need for petroleum-based gasoline by being transformed into biodiesel. Biodiesel made from used cooking oil has the potential to replace conventional diesel because it is non-toxic, biodegradable, and emits fewer greenhouse gases.

The most popular method for turning used cooking oil into biodiesel is transesterification. The process of reacting the triglycerides of waste oil with alcohol ideally methanol or ethanol with a catalyst is known as transesterification. The catalyst, usually a strong base such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), accelerates the process, producing glycerol as a by-product and fatty acid methyl esters (FAME), which are the building blocks of biodiesel. The catalyst type, temperature, reaction time, alcohol to oil ratio in moles, and the presence of water and free fatty acids in the waste oil all have an impact on the reaction's efficiency.

Before the transesterification process, waste cooking oil is pre-treated to remove water, excess free fatty acids, and contaminants that could slow down the reaction. The reaction is typically carried out at moderate temperatures (between 60 and 65°C) while being constantly stirred. After everything is finished, the mixture is allowed to settle, and the biodiesel separates from the glycerol, which is subsequently drained and cleaned for potential industrial applications.

Once the biodiesel has been separated, the purification process is finished to get rid of any remaining catalysts, extra alcohol, and undesirable by-products. A high-purity biodiesel product is produced in accordance with international fuel quality requirements such as ASTM D6751 and EN 14214 thanks to the use of water washing or dry-washing techniques. The resulting biodiesel offers a cleaner-burning and renewable fuel source that may be used in diesel engines without requiring significant modifications. The technique is even more profitable because the glycerol by-product can be utilized in the chemical, pharmaceutical, and cosmetics sectors.

Among the many advantages of turning used cooking oil into biodiesel are decreased waste, lower carbon emissions, and a decreased need on fossil fuels. To make the process more effective and profitable, however, obstacles including feedstock variability, contamination, and catalyst and processing costs must be addressed. To boost yield and reduce production costs, new advancements in enzymatic transesterification, heterogeneous catalysts, and process optimization are being made. In general, turning used cooking oil into biodiesel is a creative and practical step toward environmentally friendly energy sources.

Through the use of wet impregnation, a Zn-CaO catalyst will be created and characterized, and its effectiveness in producing biodiesel from used cooking oil will be evaluated. Advanced analytical technique like (XRD) is used to characterize the catalyst. Successful zinc incorporation in the calcium oxide matrix results from the use of XRD to determine the crystalline form and phase content of the produced catalyst. These characterization techniques are crucial for determining the Zn-CaO catalyst's physicochemical makeup, which is directly tied to its activity and production efficiency of biodiesel.

Following catalyst development, the goal of the study is to use the Zn-CaO catalyst to trans esterify waste cooking oil with methanol in order to produce biodiesel. It is justifiable to use used cooking oil as a feedstock because it converts waste into useful biofuel and is affordable. A Zn-CaO catalyst is used to react the oil's triglycerides with methanol during the transesterification process. The result is fatty acid methyl esters (FAME), sometimes known as biodiesel, and glycerol as a by-product. Using GC-MS spectroscopy, the resulting biodiesel's structural transformation into biodiesel is confirmed. GC-MS analysis provides precise molecular information on the chemical shifts and functional groups of the biodiesel, facilitating the successful transformation of used cooking oil into high-quality biodiesel. For compliance with ASTM D6751 and EN 14214 biodiesel fuel standards, key fuel characteristics like density, viscosity, flash point, calorific value, and cetane number are tested. Combustion efficiency, engine performance, and the feasibility of using biodiesel in CI engines all will influenced by these fuel properties. The results can be used to compare biodiesel made from used cooking oil to regular diesel fuel in terms of energy content, ignitability, and overall performance.

This study provides a comprehensive assessment of the feasibility of using a Zn-CaO catalyst to produce biodiesel from waste cooking oil as a fuel replacement. Through catalyst characterisation and biodiesel property analysis, this study advances the development of biodiesel technology and its practical application in the transportation and energy sectors.

5.2. CONCLUSION

The transesterification of waste cooking oil to biodiesel provides a clean, green, and sustainable answer both to waste reduction and the creation of renewable fuels. Waste cooking oil, where it is wrongly disposed and further pollutes the environment, may be easily remanufactured into biodiesel, decreasing our reliance on petroleum products. Biodiesel can be produced efficiently by the transesterification process, which uses a catalyst and alcohol to chemically convert triglycerides in oil to fatty acid methyl esters (FAME). This solves the dilemma of how to get rid of leftover cooking oil while also producing a renewable fuel supply.

Reaction conditions, feedstock quality, and catalyst selection are the three primary determinants of its success. Due to their high activity and quick reaction times, sodium hydroxide (NaOH) and potassium hydroxide (KOH) are two examples of base catalysts that are utilized. However, to prevent the creation of soap, the water and free fatty acids in used cooking oil may need to undergo an additional esterification process. While enzymatic and acid catalysts offer alternatives for managing elevated amounts of free fatty acids, they typically require longer reaction times or higher processing costs. Optimizing the reaction parameters, such as the catalyst amount, reaction temperature, and alcohol to oil molar ratio, is crucial to producing the highest possible production and quality of biodiesel.

The biodiesel so formed must undergo proper purification to conform to fuel standards like ASTM D6751 and EN 14214. Elimination of remaining catalyst, glycerol, surplus alcohol, and other contaminants is required for compliance with diesel engine compatibility. The resultant biodiesel has good attributes, such as reduced sulfur levels, increased biodegradability, and lesser greenhouse gas emissions than standard diesel. These qualities make biodiesel a cleaner and greener fuel option, supporting efforts towards mitigating climate change and ensuring energy security.

The process of turning used cooking oil into biodiesel provides financial advantages in addition to environmental ones. Utilizing waste oil as a feedstock significantly lowers production costs compared to virgin vegetable oils, making biodiesel a more affordable option. Glycerol is another by-product of the process that has use in the food processing, cosmetic, and pharmaceutical sectors. Large-scale industrialization, process optimization, and catalyst development can all help to increase the economic feasibility of biodiesel production.

In spite of its benefits, there are still challenges in the large-scale production of biodiesel as a regular fuel. Variability in waste cooking oil content, the necessity of effective pre-treatment

technologies, and compatibility problems with conventional engine designs need to be overcome in order to make it a seamless fit in today's fuel infrastructure. Technological innovation and research, such as the creation of heterogeneous catalysts, continuous flow biodiesel systems, and better purification methods, are necessary to overcome these shortcomings and improve efficiency and scalability in the production of biodiesel.

A comprehensive approach to the creation and application of a zinc-doped calcium oxide (Zn-CaO) catalyst for the biodiesel production from used cooking oil is presented in this study. Advanced characterisation methods X-ray diffraction (XRD) was used to thoroughly investigate the catalyst's structural and chemical characteristics after it was succe ssfully synthesized. These methods increased the catalytic activity of the transesterification reaction and ensured its effectiveness by certifying the incorporation of zinc into the calcium oxide matrix. The catalyst proved to be a dependable and effective method for turning leftover cooking oil into biodiesel, which offers a sustainable way to get rid of waste oil and makes it easier to produce renewable energy.

GC-MS spectroscopy was used to thoroughly examine the biodiesel made from methanol and the Zn-CaO catalyst. The test guaranteed the purity and quality of the biodiesel as well as the efficient conversion of triglycerides in waste cooking oil into fatty acid methyl esters (FAME). The biodiesel's compliance with diesel fuel regulations was ensured by the use of GC-MS, which provided valuable information regarding its chemical composition. In order to determine whether or not the biodiesel could be used in place of diesel in the transportation sector, it was carried out additional evaluations of the fuel's properties, paying attention to crucial variables such as density, viscosity, and calorific value.

According to the study's findings, zinc-doped calcium oxide is a very efficient catalyst for the production of biodiesel, offering an environmentally friendly method of turning used cooking oil into biodiesel. With favourable fuel qualities compared to conventional diesel, biodiesel made from waste cooking oil has been characterized and tested to demonstrate its viability as a fuel substitute. The results highlight the need for more investigation and improvement of biodiesel production and catalyst production, in order to advance biodiesel as a clean and renewable fuel source. Trash oil biodiesel's broad use is made possible by this research, which promotes sustainable energy sources and trash management.

5.3. RECOMMENDATION FOR FURTHER RESEARCH

Transesterification of used cooking oil can be used to make biodiesel, which can be used to produce renewable energy and manage waste. Even though the transesterification process has made great progress, more research is needed to make biodiesel production as efficient, cost-effective, and long-lasting as possible. The suggestions made for future research are as follows:

1. **Exploring unconventional catalyst and engine efficiency:**

- The performance, combustion behaviour, and emission characteristics of biodiesel can be influenced by several factors, including the type of feedstock, engine operating conditions (such as speed and load), fuel injection strategies, and the proportion of biodiesel in the blend. However, comprehensive research specifically examining waste cooking oil biodiesel across a full range of engine speeds and loads is still limited.
- Exploring unconventional catalysts like microwave-assisted, ultrasonic, or photo-catalysis may also bring new possibilities of quicker and energy-efficient transesterification.

2. **Use of Co-Products in Waste Cooking Oil:**

- Waste cooking oil tends to have a high content of impurities, e.g., free fatty acids (FFAs), which can cause problems in the transesterification reaction. Future studies need to address pre-treatment technologies that efficiently remove FFAs or utilize them in concurrent reactions, e.g., to produce higher-value co-products (e.g., soaps or glycerol derivatives).
- Investigation of integrated processes in which FFAs are also converted to other valuable chemicals as part of the biodiesel process could maximize the overall yield and efficiency of the process.

3. **Optimization of Reaction Conditions:**

- Oil to alcohol reaction temperature, time, and molar ratio are the most important parameters in transesterification. Optimizing these conditions should be the future work in order to enhance yield and reduce the energy consumption. Investigation into reaction kinetics and formulating mathematical models to determine the results from varying conditions would go a long way in ensuring optimum conditions for varying waste oils.

- Cycling of pressure and temperature may also be investigated to determine if the application of supercritical fluids (e.g., supercritical methanol) enhances the efficiency of biodiesel production.

4. **Sustainability and Economic Viability:**

- The environmental and economic effects of biodiesel production need to be further evaluated. This entails the assessment of carbon emissions, energy use, and cost evaluation of the whole production process from waste oil collection to biodiesel refining. The life cycle assessment (LCA) of biodiesel produced from waste cooking oil versus traditional biodiesel should also be included in this research.
- Scalability of the transesterification reaction for large production is also a vital study. Research on the reduction of the amount of solvent used and on waste generation through the process will make the process environmentally and financially sustainable for producing biodiesel from waste oils.

5. **Impact of Feedstock Quality on Biodiesel Properties:**

- The composition of waste cooking oils can differ greatly, and this can influence the quality of the produced biodiesel. Future research needs to examine how differences in feedstock quality (e.g., number of contaminants, fatty acid composition) influence the viscosity, oxidative stability, and cold flow characteristics of the produced biodiesel. It will be important to know how to optimize the feedstock for stable biodiesel quality for commercial use.

6. **Advanced Separation and Purification Techniques:**

- Purification of the biodiesel after transesterification is also an important step in product quality. More work on further developed separation methods, including membrane filtration, electrostatic separation, or nanofiltration, could enhance purification. This might cut the time, energy, and solvents that are now necessary for biodiesel separation, and hence make the process more efficient and sustainable.

7. **Waste Oil Collection and Supply Chain Optimization:**

- The profitability of producing biodiesel from used cooking oil directly corresponds to transportation and collection cost of the oil. Emerging areas for future studies might involve research into innovative models for collecting wastes at a low logistics cost,

like collaborating with food providers, or building localized collection systems with minimal costs.

- Studying circular economy systems through which waste cooking oil is recovered, processed, and recycled within a closed system may improve both the environmental and economic viability of biodiesel manufacturing.

8. Public and Policy Support:

- As the demand for sustainable energy continues to increase, the creation of policies that promote waste oil collection and reward biodiesel production will make the industry much more viable. Additional research on the effects of government mandates and economic incentives for producers and consumers of biodiesel from waste oil will facilitate the mass application of this technology.

Though production of biodiesel from waste cooking oil through transesterification is a very promising approach, continued research along the lines identified above is critical to improve and upscale the process. By making the technical, economic, and environmental dimensions of biodiesel manufacture better, it will be possible to develop a more sustainable and economically viable replacement for conventional fossil fuels.

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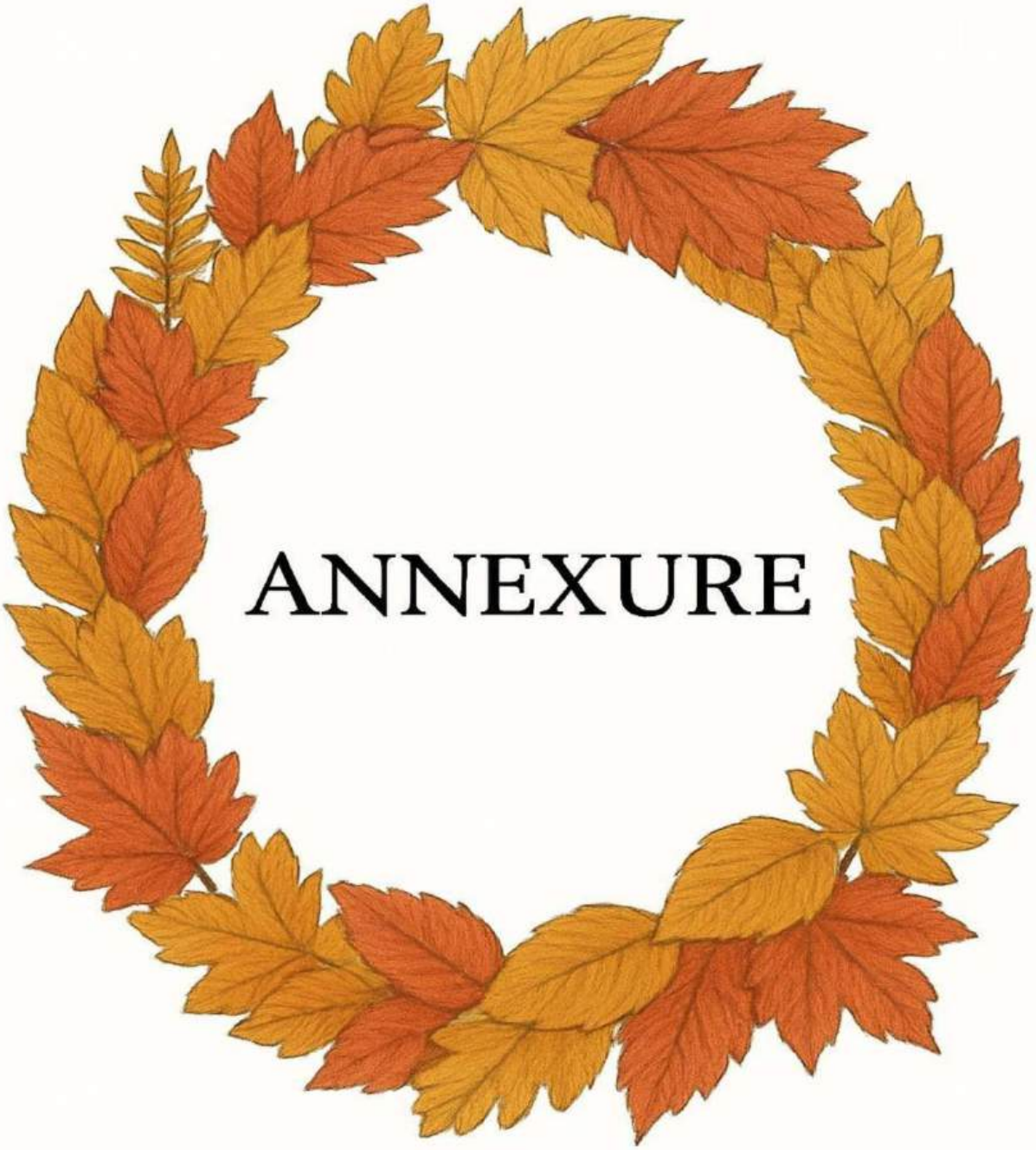
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ANNEXURE

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EXPLORING THE POTENTIAL OF WASTE COOKING OIL AS A SUSTAINABLE FEEDSTOCK FOR BIODIESEL PRODUCTION THROUGH TRANSESTERIFICATION

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ABSTRACT

This research explores the possibility of utilizing waste cooking oil as a renewable feedstock for transesterification, which is a process of converting fats and oils into biodiesel by reacting them with alcohol and a catalyst. The research was carried out in Jhansi, India, with the objective of determining the availability of waste cooking oil, the frequency of its collection, and the opinions of individuals collecting it regarding the possibility of its conversion into biodiesel. 100 respondents were asked the source of the oil, how often it was collected, and if they thought biodiesel was practical, using standardized questionnaires. It emerged that the greatest sources of used cooking oil came from home kitchens (45%) and restaurants/hotels (35%), with the commercial and residential sectors each playing a big role in the collection process. A majority of the respondents (50%) collected used oil once every week, thus ensuring a source of reliable and steady supply for the production of biodiesel. There is much hope for biodiesel potential as an alternative source of renewable fuel since 60% of the respondents said that it was highly possible to produce it from used oil. The results show that spent cooking oil can serve as a low-cost and easily accessible feedstock for the production of biodiesel and highlight the need to encourage efficient collection systems to support waste minimization and renewable energy sources.

Keywords: *Biodiesel Production, Waste Cooking Oil, Transesterification, Alcohol, Catalyst, Feasible, Alternative Fuel, Low-Cost, Renewable Energy Solutions, Reduce Waste.*

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1. INTRODUCTION

The growing energy demand worldwide and the increasing awareness of environmental degradation associated with the use of fossil fuels, biodiesel has received increasing attention as a potential renewable energy source. Biodiesel is obtained through transesterification, a chemical process that breaks down triglycerides into methyl or ethyl esters. Waste cooking oil is a by-product produced in large quantities by households, restaurants, and food processing industries, and it can be repurposed as a valuable resource instead of waste material, thus encouraging sustainability and minimizing the environmental impacts associated with its disposal.

Wastes cooking oil presents some advantages for biodiesel production because it is a readily available, free-to-cost raw material, which may also have otherwise gone to waste in much of the world, offering an economic alternative to the feedstocks that conventionally feed into biodiesel manufacturing and reduce waste with the only risk of potentially polluting landfills or waterways. Furthermore, waste oils for biodiesel can minimize the use of virgin vegetable oils. This will have a relieving effect on agricultural land and decrease its environmental footprint.

The process of transesterification is central in the conversion of waste oil from kitchen into biodiesel. In this conversion, triglycerides present in the waste oil combine with an alcohol, usually methanol or ethanol, catalyzed by a substance such as sodium hydroxide or potassium hydroxide. The reaction produces biodiesel (methyl or ethyl esters) and glycerol as a by-product.

The transesterification process has been improved significantly by researchers and industries to increase the yield and quality of biodiesel from waste cooking oil. In this respect, the generation of biodiesel from waste cooking oil can add value to waste and help in the circular economy model by reducing the environmental damage associated with waste collection.

2. LITERATURE REVIEW

Sadaf et al. (2018) focused on WCO-based transesterification to produce biodiesel. Although the tranesterification of waste oils may represent an attractive way of obtaining biodiesel very cheaply, the presence of a very large concentration of FFA significantly depresses the extent of the tranesterification. A measure of 5.5 mg KOH/g indicated high levels of acidity, i.e., FFA.

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Comparing the esterification reaction of WCO with HCl, H2SO4 and H3PO4 we have that process catalyzed by H2SO4 reduce FFA to as low as 88.8% at 60°C using a molar ratio methanol to oil 1:2.5. The transesterification with 1% catalyst of alkali (KOH) yielded FAME to the tune of 94% at 50°C. Calorie value, cloud point, pour point, specific gravity, iodine value, cetane number, acid value, and saponification value were some of the metrics used to characterised the biodiesel. There was also a Gas Chromatography (GC) examination of the biodiesel that was produced. The production of biodiesel from WCO was efficiently accomplished using alkali catalyzed transesterification, according to ASTM norms. The research showed that used cooking oils may be turned into biodiesel, which can reduce pollution and provide energy.

Yaqoob et al. (2021) analysed with an emphasis on combustion, performance, and emission parameters, as well as their influence on engine longevity. Researchers are always coming up with innovative methods to produce and use alternative, renewable, and dependable fuels because non-renewable conventional fossil fuel sources are running out at an alarming rate. Most forms of life on Earth have suffered greatly as a result of the severe degradation of the environment brought about by traditional technological practices. One of the greatest locally available alternative fuels to minimise emissions from compression ignition engines is waste cooking oil (WCO) biodiesel. Additionally, this study also reviews the economic and environmental implications. Combustion characteristics of WCO biodiesel are characterised by an increase in cylinder peak pressure value, a decrease in ignition delay period and heat release rate. There is a decline in braking power and torque, an increase in brake-specific energy consumption, and an increase in brake-specific fuel consumption when it comes to performance parameters. Because it produces 85% fewer hydrocarbon, SO2, CO, and smoke emissions in the exhaust, WCO biodiesel is an excellent environmental savior. Nevertheless, in comparison to diesel, CO2 and NOx tend to rise. Also detailed are the broader monetary effects of production on this resource's use. Our research confirms that WCO biodiesel is a great choice for any diesel engine in terms of performance, cost, impact on the environment, and fuel efficiency.

Innocenzi and Prisciandaro (2021) performed employing hydrodynamic cavitation, may set a new standard for industrial-scale uses. For biodiesel manufacturing to become a competitive process while reducing environmental effect, new and creative methods are needed. Because oil

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and alcohol are inherently incompatible as raw materials, the mixing process has a significant effect on the total process cost and operates as a bottleneck. This study presents the results of a process analysis for a biodiesel production scheme that uses virgin oil and used cooking oil as feedstocks. In the first, we model the conventional process flow; in the second, we swap out the biodiesel reactor for a hydrodynamic cavitation one. In this study, we compare the old and new processes using the life cycle costing method. This gives us a professional tool for process analysis, and it also gives us some pointers on how to apply technology in the industrial sector. The use of hydrodynamic cavitation cuts energy usage by almost 40% compared to the old method, which is an important consideration. When starting with waste cooking oil as feedstock, the costs decreased by about 60%, down to 290-300 €/t (innovative and traditional process, respectively), compared to when using virgin oil as feedstock, which ranged from 820-830 €/t.

Nayab et al. (2022) carried out in this paper to emphasize different facets of biodiesel, including biodiesel feedstocks, production methods, biodiesel qualities and characteristics, issues with and possible solutions to using vegetable oil, pros and cons of biodiesel, economic feasibility, and lastly, biodiesel's future. There needs to be research into alternative fuels to replace fossil fuels because their supply is dwindling, which could lead to an energy crisis in the future. Among the most promising new resources, biodiesel stands out. Some of the materials that have been investigated as potential feedstocks include microalgae and genetically modified plants like poplar and switchgrass; others are non-edible oils like Jatropha curcas and Calophyllum inophyllum. Diluting, pyrolyzing, micro emulsifying, and trans esterifying are some of the production processes that have been covered, along with their similarities and differences. When comparing various methods, the transesterification process stands out as the most cost-effective and productive. Transesterification methods, both catalytic and non-catalytic, provide the most environmentally friendly biodiesel production options. The catalytic potential of many catalysts, including mixed, enzymatic, homogeneous and heterogeneous acid/basic, and others, has been studied in relation to trans esterification.

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3. RESEARCH METHODOLOGY

A quantitative, descriptive research design was adopted in the study. The study involved 100 participants in Jhansi who collected used cooking oil through structured surveys. The practicality of producing biodiesel was determined by analyzing the data using frequency analysis and descriptive statistics and visualizing the results with frequency tables and graphs.

3.1. Research Design

The research design utilized here is the descriptive type for which this study investigates the feasibility of the usage of used cooking oil as sustainable feedstock in producing biodiesel. The main study of this kind intends to explore whether spent cooking oil originates, its frequency in being collected, and respondents' attitudes towards using such oil as an alternative source of feedstock for the manufacturing of biodiesel. It uses a quantitative method whereby the data is collected through surveys and analyzed using frequency distribution and descriptive statistics. The design allows for an in-depth understanding of the existing processes, attitudes, and challenges surrounding used cooking oil collection and its use in the production of biodiesel.

3.2. Data Collection

Structured questionnaires were employed as a tool of data collection on this study across participants collecting the used cooking oils for the production of biodiesel. The following crucial areas were intended to be covered by the survey questionnaire:

- **Source of waste cooking oil:** The respondents were asked to indicate if the oil came from street sellers, restaurants/hotels, industrial canteens, or home kitchens.
- **Frequency of oil collection:** The frequency of waste oil collection was indicated by the respondents, who may choose between daily, weekly, or monthly.
- **Perception of biodiesel feasibility:** Respondents said whether they thought it was highly feasible, moderately feasible, or not viable to produce biodiesel from used cooking oil.

A total of 100 respondents who actively participate in the collecting of waste cooking oil were given the survey.

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3.3. Sample Size

The study's sample size consisted of 100 respondents that were chosen from Jhansi. These respondents were specifically targeted because they were involved in the collection of used cooking oil from various sources. The sample contained diverse respondents who ensured that information was collected from different locations, including homes, eateries, workplace canteens, and street vendors. As such, due to the diverseness of the sample, a complete understanding of the various waste oil collection modes and sources in the region is achieved.

3.4. Research Area

The survey was conducted in the northern Indian city of Jhansi. This city was selected because of its diversified commercial, residential, and industrial activity. This city is a best location to test the feasibility of utilization of waste cooking oil to prepare biodiesel as there are wide sources in this city, including restaurants, industrial canteens, and kitchen areas in residential apartments. The objective of this research is to understand the dynamics of the supply chain of waste cooking oil in this region.

3.5. Data Analysis

The data collected was analyzed by making use of frequency analysis and descriptive statistics. With the help of frequency analysis, the number and percentage of respondents in each category were determined for each variable. These variables include the source of waste oil, the frequency of oil collection, and opinions regarding the viability of biodiesel. With summaries in frequency tables, clarity is further enhanced with bar charts and pie graphs (Figures 1, 2, and 3). Such data would then become readable with clear indication of trends and patterns, and the trends and patterns are all significant towards the understanding of viability in biodiesel production from used cooking oil.

4. DATA ANALYSIS AND INTERPRETATION

Table 1 and Figure 1 presents the four primary sources of used cooking oil that are collected for biodiesel production. These include: home kitchens, eateries and lodging facilities, industrial

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canteens, and street sellers. A bar graph illustration of these ratios is presented while a table for the frequency and percentage distribution for each source can be seen as well.

Table 1: Origin of Used Cooking Oil

Source	Frequency (n)	Percentage (%)
Household Kitchens	45	45%
Restaurants/Hotels	35	35%
Industrial Canteens	15	15%
Street Vendors	5	5%
Total	**100**	**100%**

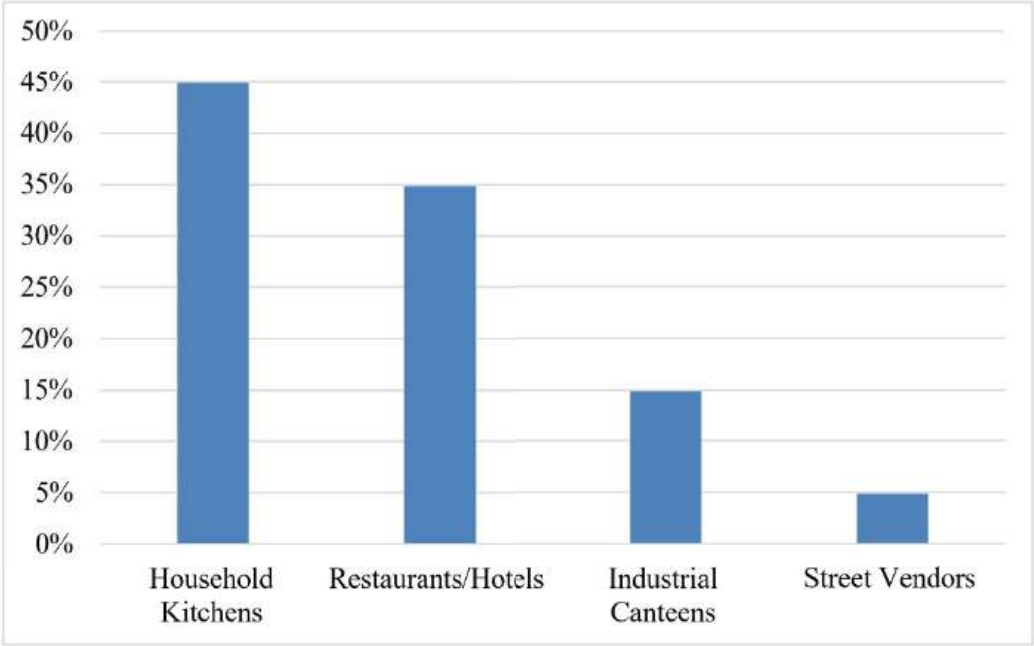


Figure 1: Graphical representation of Origin of Used Cooking Oil

Residential kitchens stand at 45% of the total sample, while restaurants and lodging facilities stand at 35%. Sellers on the streets and industrial canteens stand at 5% and 15%, respectively of the total. This has reflected the heavy potential for waste oil collection on residential and hospitality

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sectors and, therefore, focused strategies in both of these sectors can help upgrade feedstock supply for biodiesel."

The oil collection frequency for used cooking oil for the manufacture of biodiesel from respondents is depicted in Table 2. Frequency of collection of waste cooking oil provides some important insights in terms of analyzing the supply chain dynamics and the feasibility of the feedstock.

Table 2: Oil Gathering Period

Collection Frequency	Frequency (n)	Percentage (%)
Daily	30	30%
Weekly	50	50%
Monthly	20	20%
Total	**100**	**100%**

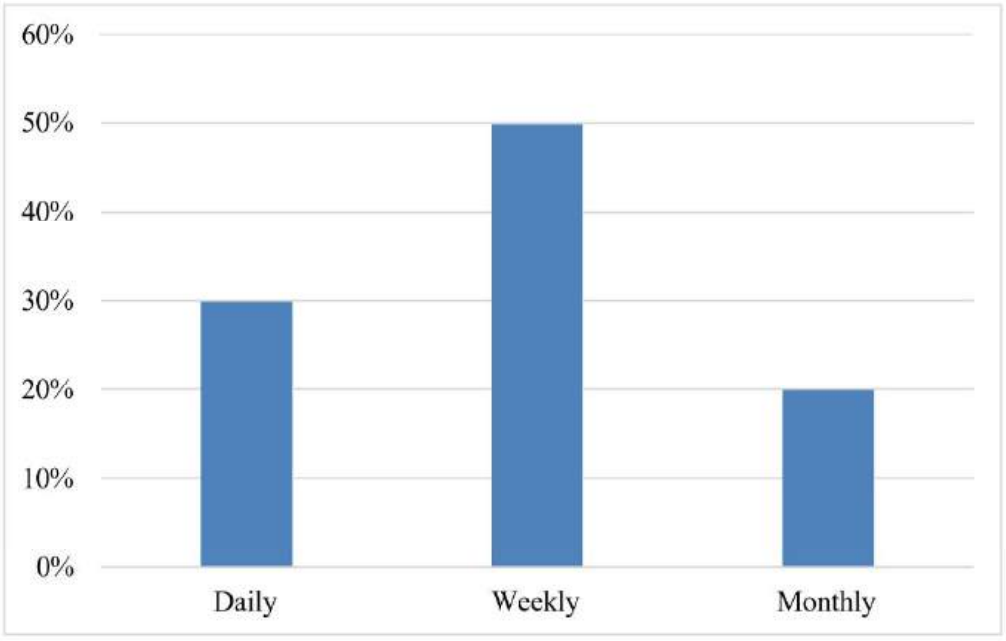


Figure 2: Graphical representation of Oil Gathering Period

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The majority of respondents (50%) gather used cooking oil once a week, according to Table 2, indicating a steady and controllable source for the manufacturing of biodiesel. Furthermore, 30% of respondents said they gather oil every day, suggesting a large, reliable supply that most likely comes from businesses like canteens and restaurants. 20%, on the other hand, collect oil on a monthly basis, which represents lower amounts, frequently from homes. The possibility of using used cooking oil as a sustainable feedstock for the generation of biodiesel is supported by these data, which collectively point to a well-distributed collection frequency.

The respondents' thoughts on the viability of turning used cooking oil into biodiesel are shown in the following table (Table 3). Their perceptions are divided into three categories: not feasible, fairly viable, and highly feasible. The frequency and percentage distribution of these viewpoints among the 100 study participants are shown in the table.

Table 3: Respondents' Perceptions of the Feasibility of Biodiesel

Opinion	Frequency (n)	Percentage (%)
Highly Feasible	60	60%
Moderately Feasible	30	30%
Not Feasible	10	10%
Total	**100**	**100%**

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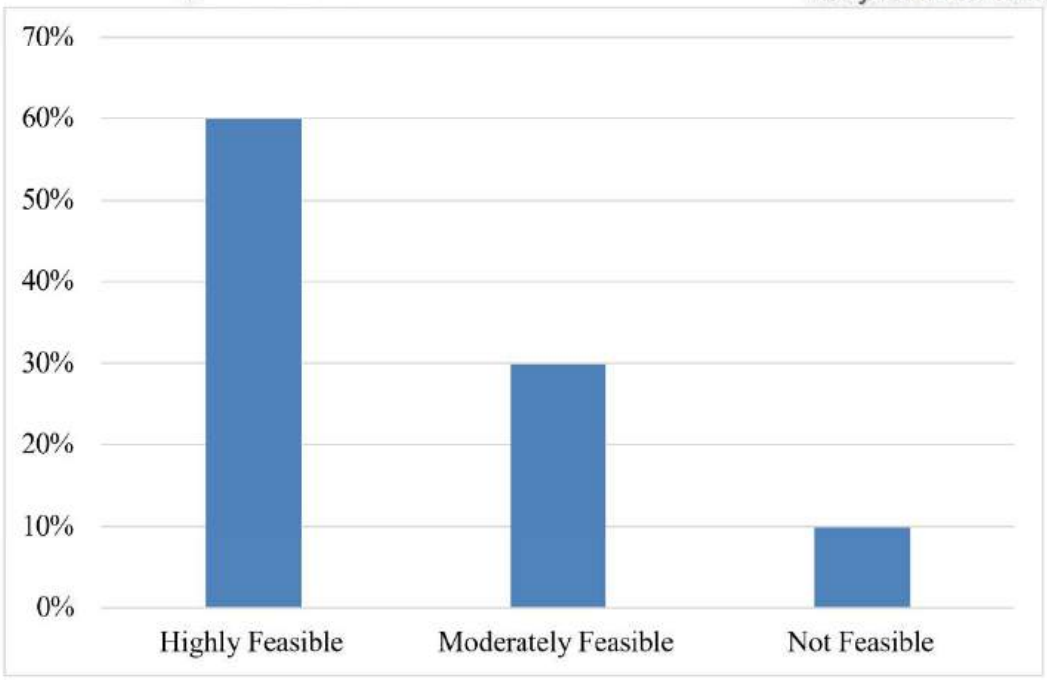


Figure 3: Graphical representation of Respondents' Perceptions of the Feasibility of Biodiesel

The majority of respondents (60%) believe that producing biodiesel from used cooking oil is very possible, according to the data in Table 3, indicating a high level of trust in the technology's potential. A further 30% think it is somewhat doable, expressing some hope but with reservations, and 10% think it is not practicable, expressing uncertainties or worries about the process's viability. This distribution shows a definite tendency towards the feasibility of using used cooking oil to produce biodiesel, with an overall optimistic prognosis.

5. CONCLUSION

This study highlights the potential of using waste cooking oil as a sustainable feedstock for biodiesel production through the transesterification process. Conducted in Jhansi, India, the study revealed that waste cooking oil is abundantly available from both residential kitchens and commercial establishments like restaurants and hotels, with a consistent collection frequency, primarily once a week. The survey results indicate strong support for the feasibility of converting used oil into biodiesel, with 60% of respondents recognizing its potential as a viable alternative fuel. These findings underscore the importance of efficient collection systems for used cooking

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oil, emphasizing its role as an affordable and accessible resource for biodiesel production, which can contribute to waste reduction, resource conservation, and the promotion of renewable energy.

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Qualitative analysis of FAMEs of Biodiesel production from waste cooking oil using GC-MS technique

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Abstract

The global energy scenario faces a change in the sea due to an increasing alarm compared to climate change, the decline in fossil fuel resources and ecological costs of traditional energy sources [1]. One of the main advantages of using WCO as raw materials to produce biological diesel is relatively low cost. Waste oil is much cheaper than pure oil, and therefore, the production of bio -diesel oil from WCO is economically possible [2]. Increasing demand for biological diesel is also supported by government incentives and policies to apply renewable energy [3] . With concerns about energy security, environmental sustainability and climate change day by day, biological diesel has become an important player in the renewable energy space. The world trending towards sustainable energy solutions, biodiesel has become a prominent option as an alternative to fossil fuels. Biodiesel, dominated by Fatty Acid Methyl Esters (FAMEs), is a biodegradable, renewable fuel made from biological materials like vegetable oils, animal fat, and waste cooking oil [4]. Pretreatment acid catalysed esterification was carried out to reduce the free fatty acid number of oil. Physicochemical parameters of waste cooking oil (WCO), such as free fatty acid (FFA) value, moisture content, saponification value, were determined to evaluate the suitability of the oil for biodiesel production. Such parameters indicate the feasibility of transesterification and biodiesel conversion with good efficiency. Waste cooking oil was trans-esterified in a 250 ml three -neck round-bottom flask followed by controlled temperature 60-65^{O}C, waste cooking oil (20 grams), methanol (95% v/v) with a molar concentration 12:1, and 5wt% catalyst (5% Zn doped CaO) was mixed together to achieve maximum biodiesel. Chemical composition analysis by GC-MS shoed the

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presence of about 82.35% fatty acid methyl esters found. Fuel properties like kinematic viscosity ,flash ,pour,fire ,cloud point,acid value FFA conversion rate, density and viscosity of biodiesel found in accordance with standard American Society testing abd Materials biodiesel specification.

Keywords: Biodiesel, Waste Cooking Oil, Transesterification, GC-MS, Fatty Acid Methyl Esters (FAMEs), Renewable Energy

1. Introduction

The burning of fossil fuels such as petroleum diesel unlocks carbon stored under the ground for millions of years, contributing to atmospheric CO_2 levels and widening global warming. On the contrary, biodiesel is made from modern biological origin sources such as vegetable oils, animal fats, and waste cooking oils. They come from crops that uptake CO_2 when photosynthesizing. Diesel ingine contribute in economic value in developing countries such engines run with petroleum diesel this petroleum diesel produces consequently, the carbon dioxide emitted when biodiesel is burned is approximately equal to the quantity already taken in by the plants that were utilized to make the fuel creating a closed carbon cycle.. This makes biodiesel especially useful in urban areas, where high traffic densities lead to increased CO levels and serious health concerns for occupants. Smoke particulate matters oxides of nitrogen oxides of carbon unburned hydrocarbon etc and they have limited resources Biodiesel, as a result of having more oxygen content, so therefore we need to move towards alternative fuel like biodiesel [5]. Favors complete combustion, thus producing reduced carbon monoxide emissions

The biodegradability and non-toxicity of biodiesel minimize the environmental impact of accidental spills, fuel leaks, and improper disposal, thus contributing to ecological conservation. Biodiesel has a high biodegradation rate based on its chemical makeup, which is mainly constituted by fatty acid methyl esters (FAMEs). Research has proven that in conditions conducive to environment (i.e., suitable temperature, microbial process, and amount of oxygen), biodiesel would be degraded three times or four times faster compared to petroleum diesel. The pollution of water sources due to WCO pollution is a serious community health risk, which can cause gastrointestinal diseases and other health problems in the community depending on water sources unreasonable treatment [6]. The entertainment of used cooking oil of drainage and discharge systems reduces the possibility of blocked drainage systems, the

destruction of pests and odour pollution. The economic and environmental advantages of WCO recycling illustrate the ability to help sustainable development as well as cleaner and more effective energy industry [7]. The waist cooking oil or frying oil is considered to be much better replacement as its price is 65% less than pure oil [8]so rather than dumping this oil without treatment it can be utilised in biodiesel formation as a cheap and efficient alternative feedstock [9]. During pre treatment methods distinct parameters a waste cooking oil contain high proportion of free fatty acids as a result of repeated frying it hinders its conversion into esters. Therefore an initial pretreatment is carried out to lower the free fatty acid content of waste cooking oil [10].Most common pretreatment procedure include heat treatment glycerol treatment and acid catalysed esterification oil with the acid values less than 1% is selected for conversion into biodiesel as it gives higher biodiesel yield[11]. Microwave assisted catalyst,enzymatic green catalyst, pyrolysis ,microemulsion and transesterification are few methods that may be used to produce biodiesel .The transesterification method for producing biodiesel is a base catalysed transterification, due to its great efficiency and relative high conversion efficiency catalyst Zn doped CaO is utilised. The advantage of using heterogenous catalyst over homogenous catalyst is that Reusability and Regeneration of Zn-CaO solid catalyst, that can be reused multiple times with minimal loss in activity whereas Homogeneous catalysts cannot be recovered and reused, leading to higher operational costs.it also this proves the limitation for produces minimal soap formation even with oils containing free fatty acids (FFA).Zn modification enhances the acid resistance of CaO, making it more effective for feedstocks with moderate to high FFA, like waste cooking oil. Methanol Is preferred among other alcohols due to a slow cost and fast reaction.Glycerol is a main byproduct of transesterification reaction which requires complete separation from biodiesel to different purification process[12].

To accurately determine the composition of biodiesel, Gas Chromatography–Mass Spectrometry (GC-MS) was used to analyze the fatty acid methyl esters (FAMEs) present in the trans esterified product. Fuel characteristics are measured by ASTM protocols and compared with the standard range provided for biodiesel[13] .Projective of this study to generate biodiesel from waste cooking oil through transistorification procedure along with the parameter optimization for its efficient utilisation in biodiesel production this present research

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work focus on chemical characterization and fuel properties analysis of obtained biodiesel by GC MS and ASTM standard protocol.

2. Materials and methods

The waste cooking oil samples were collected from different sources restaurant kitchens street vendors and shopkeepers Of Jhansi Uttar Pradesh india in dried canes and bottles all the samples were analysed by physiochemical parameters among them household kitchen Sample was found to be highly efficient for conversion into biodiesel. samples was filtered out to remove food residues left in them after cooking or frying and heated at 100 degree Celsius to remove moisture content. Ethanol distilled water beaker measuring cylinder thermometer wire mesh philtre magnetic steerer heating chamber philtre paper sulfuric acid you know and weighing machines were all needed.

2.1. Physicochemical analysis

The properties like acid value density and saponification value were analysed and performed density of waste cooking oil was measured using mass over volume formula .Acid value of sample was obtained by taking 5 grams of oil into a 50 mL conical flask. On Adding 25 mL of neutral ethanol to the flask. To dissolve oil completely mixture was warmed and stirred. On Adding 2–3 drops of phenolphthalein, the solution should remain colourless at this point (if acidic). Titration with 0.1 N alcoholic KOH solution from a burette until a light pink colour persists for at least 15 seconds (endpoint). Against this a bank was run in parallel which contained similar components except oil which was replaced by water .This would determine the acid value of the WCO.

$$\text{Acid Value (AV)} = \frac{V \times N \times 56.1}{W}$$

Where:

V = Volume of KOH used (mL)

N = Normality of KOH (usually 0.1 N)

W = Weight of oil sample (g)

56.1 = Equivalent weight of KOH

Weight of WCO sample (W) = 5.0 g

Volume of 0.1 N KOH used (V) = 5.0 mL

Normality of KOH (N) = 0.1 N

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$$AV = \frac{5 \times 0.1 \times 56.1}{5}$$

$$= 5.61 \text{mg KOH/g}$$

WCO was weighted about 5 grams into a 50 mL conical flask. On Adding 25 mL of 0.5 N ethanolic KOH to the flask that would be Attached to a reflux condenser to avoid evaporation. Mixture was heated gently on a boiling water bath for 60 minutes. It was stirred time to time to ensure complete saponification. After refluxing on adding 1–2 drops of phenolphthalein to the warm solution, the excess KOH with 0.5 N HCl was titrated until the pink colour just disappears. A blank was also run with the same volume of ethanolic KOH without oil.

$$SV = \frac{(B-S) \times N \times 56.1}{W}$$

Where:

B = Volume of HCl used in blank (50mL)

S = Volume of HCl used in sample (39.2mL)

N = Normality of HCl (0.5 N)

W = Weight of oil sample (5 g)

56.1 = Equivalent weight of KOH

$$SV = \frac{(50 - 23.1) \times 5 \times 56.1}{5}$$

$$= 151.17 \text{mg KOH/g}$$

The moisture content of waste cooking oil (WCO) was determined using the oven drying method. 5 grams of the oil sample were accurately weighed into a clean, dry crucible, and the initial weight was recorded. The crucible containing the sample was placed in a hot air oven maintained at 105 °C for 1.5 to 2 hours to allow complete evaporation of moisture. After drying, the crucible was cooled in a desiccator to prevent moisture absorption from the atmosphere, and the final weight was recorded. The percentage of moisture was calculated based on the weight loss before and after drying using the formula:

$$\text{Moisture (\%)} = \frac{\text{Initial weight} - \text{Final weight}}{} \times 100$$

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Sample weight

Free fatty acid % was also analysed simultaneously .It was found to be 2.82%

2.2. Pre-treatment

To achieve the lowest free fatty acid content acid treatment was applied on the waste cooking oil by pretreatment procedure .Acid treatment, was applied on all the waste oil samples to achieve the lowest free fatty acid (FFA)content. Esterification with the use of homogenous acids is a commonly employed procedure in which 5gm of oil was added with methanol, acid catalyst (conc. H2SO4, HCl and H3PO4) and reaction mixture was transferred to round bottom three necked flask attached with water cooled condenser placed on hot plate.

Typical reaction efficiencies of pretreatment of waste cooking oil with acid catalyst (H_2SO_4) under the specified conditions (5 wt% catalyst loading, 12:1 methanol to oil molar ratio, 60–65 °C, 5-hour reaction time. Reducing FFA below 1% makes the oil suitable for base-catalyzed transesterification.

2.3. Biodiesel conversion (Transesterification)

Pretreated waste cooking oil was transesterified in a 250 ml three -neck round-bottom flask equipped with an oil bath, magnetic stirrer, and a water-cooled reflux condenser. At a controlled temperature 60-65^{O}C, waste cooking oil (20 grams), methanol (95% v/v) with a molar concentration 12:1, and 5wt% catalyst (5% Zn doped CaO) was mixed together and continuously stirred. The catalyst was first doped with CaO and then used in transterification reaction to produce nanocrystallinity.

Wet impregnation was used to create the nanocrystalline Zn/CaO. Prepared Zinc Sulphate Solution weighing accurately $ZnSO_4$. $7H_2O$ to match the desired doping level (0.075g for 1.5% to 0.350g for 7%). Dissolved it in 10 mL of deionized water to form a clear zinc sulphate solution. Taking 5 g of CaO and suspend it in 40 mL of deionized water in a 250 mL beaker. Stirred continuously using a glass rod or magnetic stirrer to form a homogenous slurry. Slowly added the zinc sulphate solution into the CaO suspension while stirring. While continued stirring for 2–3 hours at room temperature for uniform dispersion of Zn^{2+} ions onto CaO particles. After stirring, mixture settled, and dried in an oven at 110°C for 12 hours to remove moisture. The dry mixture was then calcined for four hours at 700°C in a muffle furnace. When

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the transesterification reaction was completed the reaction share was transferred to separating funnel for overnight to separate biodiesel from glycerol layer[14].

2.4. Purification of biodiesel

The biodiesel produced through the transesterification process was subjected to purification to eliminate residual catalysts, unreacted methanol, and soap content. Both wet and dry washing techniques were employed to achieve a clean final product. In the wet washing method, water was heated to 60 °C and used to repeatedly wash the biodiesel until a clear, distinct product layer was formed. The purified biodiesel layer was then dried by heating at 100 °C to remove any remaining moisture [15].For the dry wash method, silica was used as an adsorbent to eliminate impurities. Approximately 5% silica by weight was added to the biodiesel and the mixture was gently stirred at 60 °C for two hours. Following this, the mixture was left undisturbed to allow the silica to settle at the bottom. The purified biodiesel layer was then carefully separated from the settled adsorbent [16].

2.5. GC-MS analysis

GC-MS is a widely accepted technique for the qualitative and quantitative assessment of individual fatty acids, offering high sensitivity and precise identification of molecular structures.

The GC-MS analysis was performed using an Agilent 7890B gas chromatograph coupled with a 5977A mass spectrometer. The FAMEs were separated on a DB-WAX capillary column (30 m × 0.25 mm ID × 0.25 µm film thickness)was used. Helium act as carrier gas used at a constant flow rate of 1.0 mL/min,lnjection Volume of sample 100 µL in 900 µL (split ratio 10:1)of chloroform solvent in an Eppendorf taken .Column Temperature Program was Initially maintained at 60°C (held for 2 min) and then increased to 350°C at 10°C/minutes to Final ramp at 400°C at 5°C/min (held for 10 min).The column Injector Temperature was set at 250°C MS Conditions were Electron Ionization (EI) mode at 70 eV, scan range 50–550 m/z,IS standard -Palmitic acid Molecular weight= 650, mass=1mg in sample (biodiesel) 20mg of weight was used to measured.

2.6. Fuel properties analysis

The fuel properties of biodiesel such as kinematic viscosity carbon residue test cloud port flash point fire point were determined according to the astm protocols carbon residue of sample was measured by using Conradson carbon residue apparatus, flash point by Pensky Martens closed

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cup tester,calorific value by bomb calorimeter,kinematic viscosity by viscometer and ash content in a muffle furnance.

3. Results and discussion

3.1 Physical properties of waste cooking oil

Waste cooking oil exhibits altered properties compared to pure oil, as it is repeatedly used for frying at high temperatures. These changes in characteristics vary among different waste oils, depending on the frequency of heating, the peak temperatures reached, and the type of food cooked in the oil. Waste cooking oil was Collected from household kitchens was found to be have different density with acid value as well as saponification value due to access hydrolysis and polymerization reaction. Density and saponification value of samples were 919 kg/m^3, 151.17 mg KOH/g and moisture content was 0.29%.

Table.1 Physicochemical Properties of Waste Cooking Oil (WCO)

Parameter	**Measured Value**
Acid Value	5.61
Moisture Content (wt.%)	0.29
Saponification Value (mg KOH/g sample)	151.17

3.2 pretreatment

Waste cooking oil sample was treated with pretreatment procedure and the acid value of oil after the methods are given in the table 2 it was found to be lower Acid value with acid treatment and free fatty acid content was found to be less than before and it was found to be free fatty acid conversion rate about 84% that would be better to use for further transfer reactions.

Table 2. parameters for waste cooking oil samples after pre-treatment procedures.

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Parameter	Before Pretreatment	After Pretreatment
Acid Value (mg KOH/g)	5.61	**0.9**
FFA (%)	2.82%	**0.45%**
FFA conversion rate	——	**84%**

3.3 Characterisation of biodiesel

Transesterification procedure was catalysed by using zinc doped calcium oxide catalyst and physical and chemical parameters were observed on final biodiesel yield. The physical properties of biodiesel derived from waste cooking oil were evaluated, including kinematic viscosity, density, flash point, calorific value, ash content, and carbon residue. These properties were then compared with those of conventional diesel fuel based on ASTM standard protocols. The refined biodiesel exhibited a higher density (approximately 872 kg/m³) compared to the typical diesel range of 830–860 kg/m³. Its kinematic viscosity was also higher at 5.57 mm²/s, while diesel generally falls within 1.9–4.1 mm²/s. Due to this higher viscosity, biodiesel from recycled cooking oil is often blended with diesel to enhance performance. The flash point—defined as the temperature at which a fuel emits vapours that can ignite in air—was also notably higher for biodiesel, measured around 152 °C, compared to diesel's minimum standard flash point of 52 °C. A higher flash point indicates safer handling, storage, and transportation characteristics. The measurements of these and other relevant fuel properties are summarized in Table 3.

Table 3. fuel properties for Zn doped CaO catalysed biodiesel compared to pure diesel on ATSM protocols.

Property	Typical Range of diesel ASTM std.	biodiesel
Density @31°C	830–860	872kg/m³

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Kinematic Viscosity @40°C	1.9–4.1 mm²/s	5.5 cSt
Flash Point	≥ 52 °C	152 °C
Cloud Point	-15 to +5 °C (varies)	5
Pour Point	-35 to 0 °C (varies)	2
Carbon Residue	≤ 0.35% (by mass)	0.04%
Ash Content	≤ 0.01% (by mass)	0.02%
Fire Point	~65–96 °C	164
Calorific value	~45,000–46,000 kJ/kg	38 MJ/kg

3.4 Impact of reaction time on Biodiesel

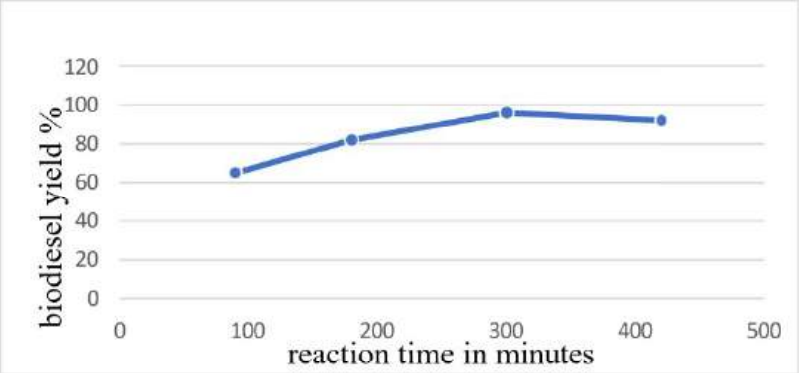
The transesterification reaction was tracked for different time periods—90 minutes, 180 minutes, 300 minutes, and 420 minutes—to find out the time needed for the reaction to achieve equilibrium. The yield of biodiesel was quantified at every time interval, and the progress of the reaction was monitored by withdrawing samples of the reaction mixture at intervals. The reaction conditions like the methanol-to-oil molar ratio (12:1), catalyst loading (5 wt%), and temperature (60–65°C) were maintained constant during the experiment. By monitoring the conversion of waste cooking oil (WCO) to biodiesel at different time intervals, the research intended to determine the optimum reaction time required to obtain maximum biodiesel yield and determine the time taken to attain equilibrium in the process of transesterification.

The conversion was 65% at 90 minutes, 82% at 180 minutes, 96% at 300 minutes, and 92% at 420 minutes, showing that the reaction was close to completion. Beyond 90 minutes, prolonging the reaction time to 180 minutes only slightly increased the yield (82%), which indicated that the reaction had almost reached equilibrium at 180–300 minutes. Thus, a reaction time of about 300 minutes was found to be ideal for maximum biodiesel yield since prolonging the time further offered insignificant advantages and would only consume unnecessary energy. Yield of biodiesel rose constantly with reaction time, achieving a level of about 65% conversion at 90 minutes and 82% at 180 minutes. Exceeding 300 minutes, a further prolongation of the reaction time up to 400 minutes resulted decrease in a (96%), reaction proving that by 300 minutes, the reaction was practically at the stage of equilibrium. Thus, an

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optimal duration of reaction around 300 minutes is adequate to produce the highest biodiesel content without wastage of energy.

Figure 1. Effect of reaction time on biodiesel yield

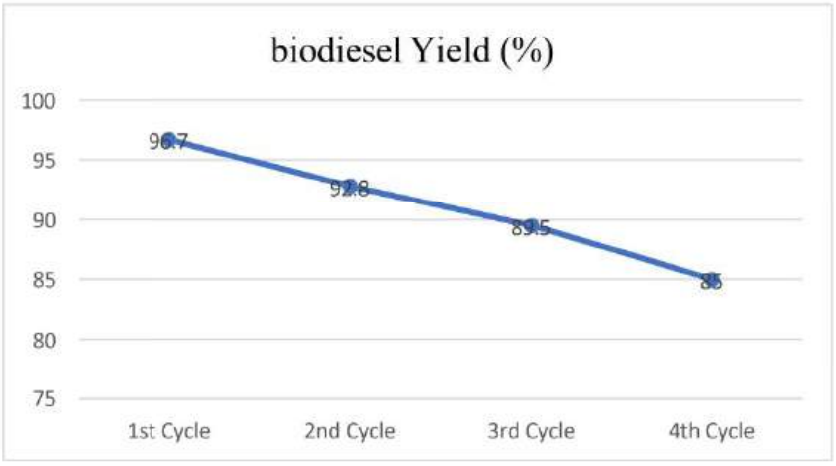


3.5. Impact of reusability of catalyst

The reusability of the 5-Zn/CaO-700 catalyst was investigated through successive transesterification reaction using the catalyst for repeated cycles.The 5-Zn/CaO-700 catalyst had outstanding catalytic activity for the initial three cycles, producing biodiesel yields of 96.7%, 92.8%, and 89.5%, respectively. This indicates that the catalyst was still efficient for multiple uses with minimal drop in yield between the first and second cycles. However, a significant reduction in yield to 85.0% was noted in the fourth cycle after the third cycle, reflecting some level of catalyst deactivation. This reduction in yield is thought to result from loss of active sites or changes in structure of the catalyst following repeated use, which restricted its performance. In spite of this, the catalyst was highly recyclable for three cycles and showed promise for sustainable biodiesel production with very little loss of efficiency.

figure 2.: Effect on biodiesel yield on reusability of 5-Zn/CaO-700 catalyst in successive transesterification cycles

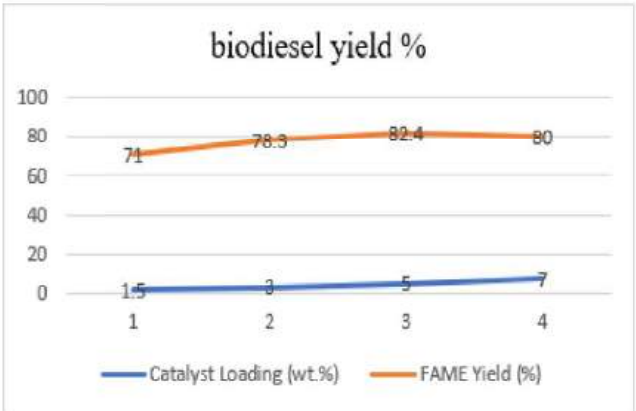
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3.6. Impact of catalyst loading

Loading of catalyst greatly impacted the yield of biodiesel. The yield was increased by raising the loading from 1.5 wt% to 5 wt%, with 5 wt% yielding the highest biodiesel production (82.4%). If the loading was further increased to 7 wt%, however, yield decreased (80%) because of mass transfer restrictions and rising mixture viscosity, which makes 5 wt% the best catalyst loading for effective transesterification.

Figure 3. Effect of catalyst loading on biodiesel yield%.

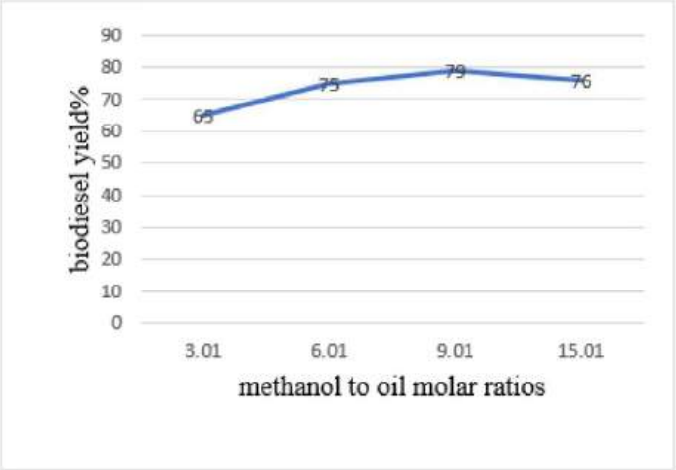


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3.7. Impact of methanol to oil molar ratio on biodiesel yield

The methanol-to-oil molar ratio is a critical factor in the transesterification process, as it significantly influences the formation of fatty acid methyl esters (FAMEs). Determining the optimal molar ratio is essential for maximizing biodiesel yield while minimizing production costs. In the case of heterogeneous catalysis, various molar ratios—3:1, 6:1, 9:1, and 12:1—were tested given in fig(4). Among these, the most effective ratios were found to be 9:1 and 12:1.Under catalytic conditions, methanol reacts readily with triglycerides at a temperature range of 60–65 °C, completing the reaction within 300 minutes. A 12:1 molar ratio produced the highest biodiesel yield of 82.3%. However, increasing the methanol ratio beyond 12:1 led to incomplete reactions due to difficulties in separating glycerol, some of which remained in the biodiesel phase. This residual glycerol lowered the apparent yield and affected the purity of the final product

Figure 4. Effect of methanol to oil molar ratio on biodiesel yield



3.8. Gas chromatography

Gas chromatography (GC) is a highly efficient analytical technique widely used for both qualitative and quantitative assessments due to its rapid analysis time and high resolution. In this study, the waste cooking oil underwent multiple rounds of washing and purification prior to conversion, and the final yield was analyzed using GC-MS. As illustrated in the figure, GC-MS effectively identified the major components present in the waste cooking oil, offering valuable insight into the success of the purification process before biodiesel production.A total of seven distinct components were identified through GC-MS based on their chemical composition. This technique enabled precise separation and detection of individual

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compounds, including various fatty acids, glycerides, and lipid-related substances. The identification of these components is critical in assessing the oil's quality, level of purity, and the presence of any residual contaminants or impurities.The integration results, presented in Table 5, include details such as retention time, area percentage, and peak height for each compound.

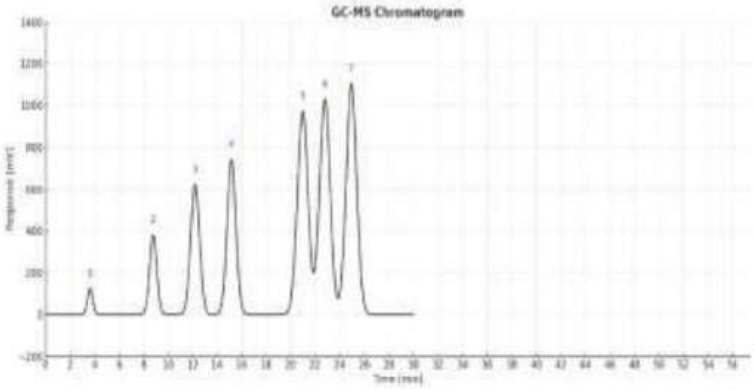


Table 5. The details of integration results.

Compound Name	Height (mV)	Retention time	Area %	wt. %
1.Methyl heptanoate (C7:0)	123.17	3.625	2.48%	1.28%
2.Methyl tetradecanoate (C14:0)	378.13	8.755	7.60%	6.59%
3.Methyl pentadecanoate (C15:0)	623.72	12.162	12.54%	11.50%
4.Methyl hexadecanoate (C16:0)	742.31	15.202	14.93%	14.44%
5.Methyl linoleate (C18:2)	1028.38	22.448	20.69%	21.77%

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6.Methyl oleate (C18:1)	1103.25	24.963	22.19%	23.52%
7.Methyl stearate (C18:0)	973.21	21.529	19.57%	20.90%
Total	**5230.23**		**100.00**	**100.00**

Higher ester content, particularly fatty acid methyl esters (FAMEs), indicates a successful transesterification reaction and good-quality biodiesel with minimal side-product formation. The measured FAME content was used to evaluate the biodiesel yield and overall conversion efficiency. The methyl ester content of the biodiesel sample was calculated based on the area percentage obtained from GC-MS analysis, using the following formula:

$$\text{Methyl Ester Content (\%)} = \frac{\text{Methyl Ester Area (\%)} \times \text{Weight of the Product (g)}}{\text{Weight of the feedstock used(g)}}$$

Methyl Ester Area (%) = 97.52

Weight of the Product = 16.9 g

Weight of the Feedstock = 20 g

$$\text{Methyl ester \%} = \frac{97.52 \times 16.9}{20} = 1647.088$$

$$= 1647.088 / 20 = 82.3544$$

The methyl ester content of the biodiesel sample was found to be 82.35%. Overall these findings suggest that biodiesel produced from this cooking oil can be a promising alternative fuse source to reuse the environmental impact of traditional diesel fuel.

Conclusion

This research demonstrated that waste cooking oil serves as an efficient and cost-effective feedstock for biodiesel production. Key reaction parameters—including reaction time, catalyst concentration, and methanol-to-oil ratio—significantly influenced both the yield and the properties of the final biodiesel product. GC-MS analysis confirmed a high concentration of fatty acid methyl esters (FAMEs), indicating successful transesterification. Furthermore, the produced biodiesel exhibited favourable fuel properties that align with ASTM standards. When compared with conventional diesel, biodiesel showed notable improvements in performance characteristics. The findings suggest that biodiesel production from waste cooking oil is not only technically viable but also economically and environmentally sustainable. Since waste cooking oil can be collected from household and commercial kitchens at little to no cost, this approach reduces overall production expenses. Additionally, it helps lower greenhouse gas emissions and promotes the reuse of a valuable resource that would otherwise be discarded, supporting cleaner energy initiatives.

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Disclosure statement

No potential conflict of interest was reported by the author(s)

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