Review Article

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Comprehensive Review of Biodiesel Production from Non-edible Feedstocks: Environmental Impacts and Sustainable Solutions

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ABSTRACT

The pursuit of sustainable alternatives to fossil fuels has led to extensive research into biodiesel production and its compatibility with internal combustion (IC) engines. This review paper provides a comprehensive analysis of biodiesel synthesis methodologies using non-edible oil sources, focusing on their feasibility, efficiency, and environmental impact. Various non-edible oil feedstocks, such as rubber, jatropha, pongamia, and camelina, are evaluated for their potential as biodiesel precursors, considering factors such as availability, lipid content, and cultivation requirements. Furthermore, this review delves into the synthesis processes, including transesterification and esterification, highlighting recent advancements and challenges in improving reaction kinetics and yield. The characterization techniques employed to assess biodiesel quality, such as physicochemical properties and spectroscopic analysis, are also discussed. Additionally, the paper examines the compatibility of biodiesel derived from non-edible oils with IC engines, addressing issues related to engine performance, emissions, and durability. Comparative studies between biodiesel blends and conventional diesel fuel are presented, elucidating the effects on combustion characteristics, engine efficiency, and pollutant emissions. The potential of biodiesel to reduce greenhouse gas emissions and mitigate environmental pollution is explored, along with challenges associated with large-scale implementation and commercialization. In conclusion, this review provides valuable insights into the synthesis of biodiesel from non-edible oil sources and its compatibility with IC engines, offering a roadmap for future research directions and technology advancements in the pursuit of sustainable energy solutions.

Keywords: Non-edible feedstocks; Biodiesel; Production; Characterization; Engine testing.

1. INTRODUCTION

The rising global energy demand and environmental concerns have driven the search for sustainable alternatives to fossil fuels. Biodiesel, made from renewable resources like vegetable oils and animal fats, offers a promising solution to reduce fossil fuel's impact on climate and air quality. While biodiesel from edible oils is well-researched, using non-edible oils provides a viable way to address food security and expand biodiesel production (Singh *et al*. 2024; Elendu *et al*. 2024). Non-edible oil sources, including jatropha, pongamia, camelina, and others, offer promising alternatives for biodiesel synthesis due to their abundance, low competition with food crops, and suitability for cultivation in marginal lands (Ferreira Mota *et al*. 2022). Converting non-edible oils into biodiesel requires transesterification or esterification, producing fatty acid esters (FAME/FABE) for diesel use. The key factors for efficient production include selecting the right catalysts, optimizing reaction conditions, and refining the process (Yusuff *et al*. 2023). Integrating biodiesel into current transportation systems depends on its compatibility with internal combustion engines. The major factors include engine performance, emissions, and durability with biodiesel blends. Compatibility testing is crucial to evaluate these effects across various blends and engine types (Gzate *et al*. 2024).

This review aims to provide a comprehensive overview of biodiesel synthesis from non-edible oil sources and its compatibility testing in IC engines. It examines the current state of research, recent advancements, challenges, and future prospects in both biodiesel production and engine compatibility testing. By elucidating the synergies between biodiesel synthesis from non-edible oil sources and its utilization in IC engines, this review seeks to contribute to the advancement of sustainable energy solutions and the transition towards a low-carbon transportation sector.

2. BIOENERGY

Burning large amounts of fossil fuels harms the environment and living organisms. Renewable bioenergy is seen as a sustainable alternative. Biomass from second-

generation biofuels, which can produce solid, liquid, and gaseous fuels for transportation, industry, and electricity, has gained popularity. Advanced physical, chemical, and biological processes are used to generate bioenergy. In India, crop biomass, estimated at 500 million metric tonnes annually, can produce 18,000 megawatts of bioenergy.

2.1 Historical Background

Biofuels, made from biomass, have been used since the 19th century, with transesterified vegetable oils gaining early attention. Common biofuels include biodiesel and bio-alcohols like bioethanol and biobutanol. Rudolf Diesel's invention in 1885 highlighted the potential of vegetable oils as engine fuel (Murugesan *et al*. 2012). The 1970s energy crisis and the 1973 Gulf Oil Crisis spurred global research into alternative biofuels, including hydrogen, LPG, alcohols, and CNG. While alcohols are unsuitable for diesel engines and vegetable oils for petrol engines, biodiesel offers a viable solution (Banapurmath *et al*. 2008).

3. BIODIESEL

Biodiesel, made from vegetable oils and animal fats, is a renewable, biodegradable, and low-emission alternative to diesel fuel. Although Rudolf Diesel experimented with vegetable oil as fuel in the early 20th century, cheaper petroleum led to the rise of diesel fuels. Vegetable oils were occasionally used during the 1930s and 1940s, mainly in emergencies. Today, biodiesel is gaining popularity due to rising crude oil prices, dwindling fossil fuel reserves, and environmental concerns. Increased petroleum use will worsen air pollution and CO_2-related global warming. Biodiesel can reduce pollutants and carcinogens, especially in enclosed environments like underground mines. Fats and oils (triglycerides) from plants and animals are hydrophobic compounds made of glycerol and fatty acids, with varying carbon chain lengths and unsaturated bonds. These triglycerides and fatty acids influence biodiesel's chemical and physical properties. Fatty acids can be saturated (single carbon-carbon bonds) or unsaturated (one or more double bonds). Key fatty acids in feedstocks include oleic, linoleic, palmitic, and stearic acids. Other fatty acids such as erucic, palmitoleic, arachidic, and myristic acids are also present. Trace amounts of phospholipids, tocopherols, sulfur compounds, and carotenes may also be found (Ong *et al*. 2013).

3.1 Advantages of Biodiesel

Biodiesel, made from renewable sources like vegetable oils and animal fats, offers many benefits. It reduces greenhouse gas emissions, improves air quality by emitting less sulfur and particulates, and can be produced domestically, promoting energy independence and economic stability. Biodiesel is compatible with diesel engines, requiring minimal adjustments, and is biodegradable and non-toxic, lowering spill risks. Overall, it presents a cleaner, more sustainable alternative to conventional diesel, with environmental and economic advantages. Biodiesel is a renewable, non-toxic fuel and worsens quicker than diesel.

- The presence of oxygen advances the ruin reaction.
- Biodiesel blended with diesel increases the efficiency of engine.
- The increase in combustion reaction and the drop in oxidation potential is due to the improved oxygen presence of biodiesel.
- Biodiesel has much lubrication property when related to that of petroleum-based diesel fuel.
- They are domestic, inexhaustible energy source and energy content is closely related to diesel fuel.
- Biodiesel from second generation crops decrease the environmental issues.
- Biodiesel is carbon neutral because plants absorb more CO_2 through photosynthesis than they release when used as fuel in engines.
- It assists in reducing the dependence of crude oil imports and helps improve agricultural activities by providing employment.
- The storing, transportation and handling risk is much lower than petroleum-based diesel.
- The by-product, crude glycerol obtained from the production of biodiesel, may be used for the production of industrial, cosmetics as well as medical based chemicals.

3.2 Disadvantages of Biodiesel

While biodiesel has several advantages, it also has notable disadvantages. A major concern is its competition with food production, as feedstocks like soybean and palm oil can drive up food prices and lead to land use conflicts. Additionally, growing these crops may contribute to deforestation, particularly in biodiverse areas like the Amazon. Biodiesel production often requires significant water and energy, raising resource depletion concerns. Its performance in cold weather is also inferior to conventional diesel, requiring engine modifications or blending. Although biodiesel emits fewer greenhouse gases, its lifecycle emissions vary based on feedstock production and transport, necessitating careful assessment. Addressing these challenges through sustainable sourcing and technology advancements is essential for biodiesel's promise as a renewable fuel.

- Viscosity may be higher for biodiesel.
- Copper strip corrosion also reported in some cases.
- On energy basis, fuel economy is slightly reduced.

- Unfavourable cold flow properties cause the fuel to gel at very low temperatures, making it difficult to pump from the fuel tank to the diesel engine.
- Since the density is higher than that of petroleum-based fuel, custom blending is required under sub-freezing conditions. Oxidation is a major disadvantage and in progressive stages, it causes fuel acidity condition and forms sediments and gums which clog the filters.
- Due to reduced vegetable oil production, biodiesel is more expensive.

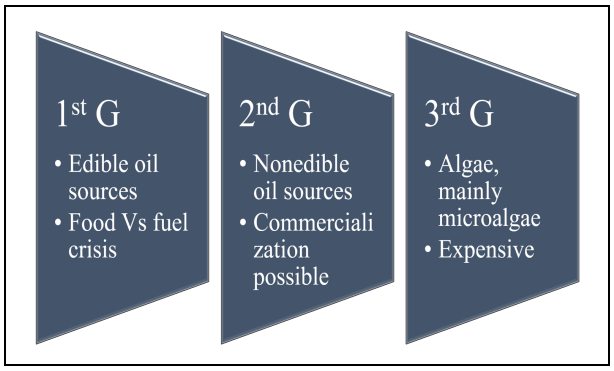


Fig. 1: Three generation feedstocks and their advantages and limitations

4. GENERATIONS OF BIODIESEL

Biodiesel feedstocks have evolved to improve sustainability and efficiency. The first generation relied on edible oils like soybean and palm oil, raising concerns about food competition and environmental impact. The second generation focused on non-edible oils, waste oils, and animal fats to address these concerns, though scalability and cost issues limited adoption. The third generation, still in development, explores advanced feedstocks like microalgae and genetically modified crops, offering high lipid content and rapid growth but requiring further research. Each generation aims to create more sustainable, efficient feedstock options to meet the demand for renewable fuels.

- First generation
- Second generation
- Third generation

4.1 First Generation

The demand for edible plant oils for biodiesel has led to a fuel vs. food crisis. First-generation sources like rapeseed, palm, soybean, and sunflower oils may cause food price hikes, hunger, and deforestation. As a result, using edible oils for biodiesel is discouraged, prompting researchers to seek cheaper, non-conflicting alternatives (Xie and Zhao, 2014).

4.2 Second Generation

In this context of use, non-edible feedstocks play a vital massive attraction. These sources have higher amount of oil and are easily available and they grow up in non-fertile lands, which are not fit for agriculture activities. The second generation bioresources include rubber seed oil, jatropha oil, jojoba oil, karanja oil, linseed oil, cotton seed oil, pongamia oil, etc, (Fig. 3) that destruct the contest between fuel and food. Also, they do not impact the food requirement, they are adequate enough to replacee the vast requirement of transportation fuel (Kumar *et al*. 2013).



Fig. 2: Edible feedstocks a) Soybean and b) Sunflower

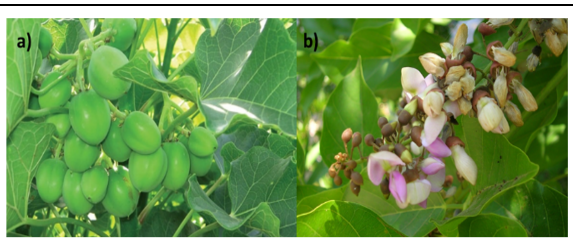


Fig. 3: Non-edible vegetable feedstocks a) Jatropha seed and b) Karanja seed

The oil residue left after cooking is typically discarded without any alternative use, leading to environmental contamination. It is impure and contains high levels of free fatty acids, which complicate the biodiesel conversion process. Animal fats such as chicken fat, fish fat, beef and duck tallow are considered as expected feedstock source for biodiesel making, but biofuel conversion is instead difficult because of its considerable quantity of saturated fatty acids. Also, they were minimal resistant to rust process because of the absence of antioxidants (Kwon *et al*. 2014).

Most previous feedstocks are unsustainable for mass production. Algae, considered third-generation feedstocks, fix atmospheric CO_2 and have higher oil yields with less land use (Fig. 4). Macroalgae, or seaweeds, are fast-growing freshwater and marine plants that can reach 60 meters in length. Microalgae, compared to bacteria, fungi, and yeast, contain more oil. Gravity and centrifugal sedimentation methods for biomass harvesting are based on Stokes' law. Gravity

sedimentation, typically used for wastewater treatment, works for larger microalgae. Centrifugal sedimentation uses centrifugal force to recover biomass quickly, easily, and non-disruptively, even for high-value enzymatic products. The centrifuge choice depends on harvesting efficiency and particle size, with types including nozzle, solid-ejecting disc, solid bowl decanter, and multichamber. The main drawbacks are equipment maintenance and high energy demands. (Bosma *et al*. 2003).

4.3 Third Generation

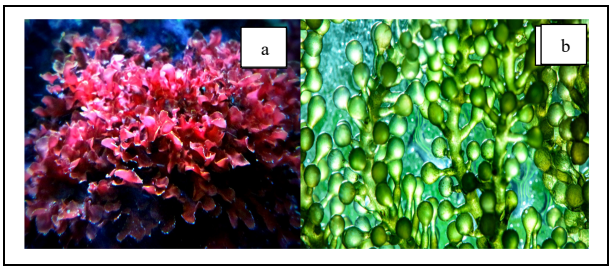


Fig. 4: Third generation feedstocks (a) macroalgae and (b) microalgae

5. OIL TREATMENT TECHNIQUES

Normally vegetable oils have high viscosity and low volatility which are the major issues connected to their application. Some strategies for overcoming these challenges include heating, blending, gasification, thermochemical liquefaction, micro-emulsion, pyrolysis and transesterification reaction for used as biodiesel in an engine (Fig. 5).

5.1 Heating

The viscosity of vegetable oils will be decreased by warming them before injection. The viscosity of vegetable oils can be reduced by preheating them to around 55°C, making them comparable to diesel fuel. This improves the engine's fuel–air mixture preparation and spray characteristics. Preheated vegetable oils also perform better and result in lower emissions (Gürü *et al*. 2010).

5.2 Blending

Engines can run on a 10% vegetable oil blend without modification, though replacing 100% of gasoline with vegetable oil isn't yet feasible. Blends of 20% vegetable oil and 80% gasoline are possible, and short-term experiments with a 50% jatropha oil blend in gasoline engines have shown no major issues. However, more research is needed for long-term use. Higher vegetable oil blends are generally unsuitable for diesel engines due to issues like high viscosity, oxidation, carbon deposits, and oil thickening (Pramanik 2003).

5.3 Gasification

When biomass is allowed to react with oxygen and water to create syn gas (a mixture of CO, H_2, CO_2, N, and CH_4) at high temperatures (800 -1000°C), this process is known as gasification. According to reports, 1 g of spirulina biomass produced 0.64 g of methanol at a temperature of 10,000°C (Hirano *et al*. 1998).

5.4 Thermochemical Liquefaction

In the presence of hydrogen and a catalyst, thermochemical liquefaction converts wet microalgal biomass into liquid fuel at low temperatures (300-3500°C) and high pressures (5-20 MPa). Due to the complicated fuel feed system, this method is quite expensive, but it breaks down biomass into tiny molecules with the highest possible energy density (Patil *et al*. 2008).

5.5 Micro-emulsion

Vegetable oils have high viscosity, prompting research into micro-emulsions using solvents like methanol, ethanol, and 1-butanol to address this issue. Micro-emulsions are colloidal dispersions with dimensions between 1 and 150 nm, formed spontaneously from two typically incompatible liquids. They improve spray properties through explosive evaporation of low-boiling elements. Despite having lower cetane numbers and energy content than diesel, micro-emulsions of aqueous ethanol in soybean oil performed comparably (Srivastava and Prasad 2000).

5.6 Pyrolysis

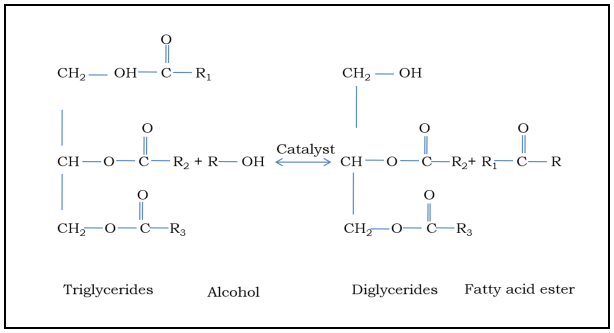
Pyrolysis is the process of transforming materials using heat and a catalyst. It has been applied to vegetable oils, animal fats, fatty acids, and methyl esters. For over 100 years, researchers, especially in areas lacking petroleum, have studied pyrolysis of fats to produce diesel engine fuels. Pyrolysis of triglycerides produces alkanes, alkenes, aromatics, and carboxylic acids (Ma and Hanna 1999).

5.7 Transesterification

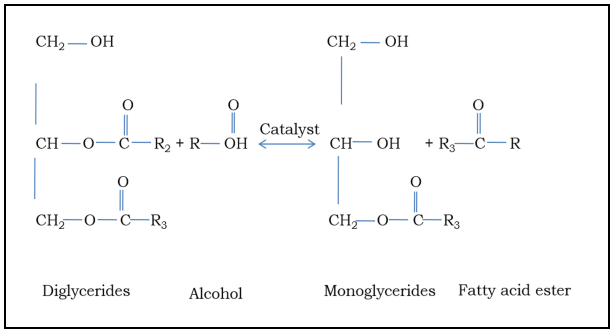
Transesterification is the process in which the alkoxy group of an ester is replaced by an alcohol, typically in the presence of an acid or base catalyst. While blending, micro-emulsion, and pyrolysis are used for short-term tests of vegetable oils, transesterification is essential for producing biodiesel from bio-lipids for long-term use. In this reaction, triglycerides combine with alcohol to form esters and glycerol (Murugesan *et al*. 2012). Numerous researchers claimed that ethanol and an alkali catalyst can be used for transesterification

(Demirbas 2007). The previous findings indicate that methyl esters are a good substitute for diesel fuel; however, ethyl esters have received far less attention. Therefore, various investigations were conducted to produce bio-diesel utilising ethanol rather than methanol. The chemistry of transesterification in methanolysis and ethanolysis is identical. The method is carried out similarly to that of methanolysis, and an alkaline catalyst is employed. The steps involved in transesterification are

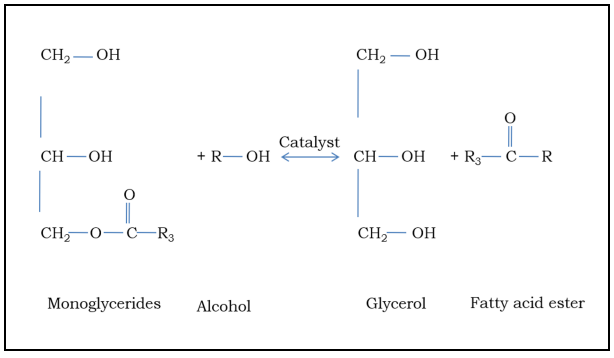
Step 1: Formation of Diglycerides



Step 2: Formation of Monoglycerides



Step 3: Formation of Fatty Acid Alkyl Ester



The use of MgO impregnated with KOH as a heterogeneous catalyst for the transesterification of mutton fat with methanol was investigated. This process produced more than 98% biodiesel within 20 minutes (Saravanan *et al*. 2020). Researchers converted inedible animal tallow into bio-diesel by preheating it between 105°C and 110°C prior to transesterification to get rid of contaminants and bubbles (Öner and Altun, 2009). The two-step catalytic technique for the manufacture of biodiesel from chicken waste oil with synthetic magnesium (Mg) additive was utilized (Gürü *et al*. 2010). Magnesium-based additives were used to lower biodiesel's pour point, flash point, and viscosity, while H_2SO_4 and NaOH catalysts accelerated the reaction. Radio frequency heating helped produce 97.7% biodiesel from beef tallow. Fats, oils, and grease were recovered and pre-treated for biodiesel production, with H_2SO_4 proving more effective than ferric sulfate as a catalyst for converting FFA to fatty acid methyl esters. Biodiesel from bitter almond oil achieved a 90.8% yield using 0.9% KOH (Atapour and Kariminia, 2011).

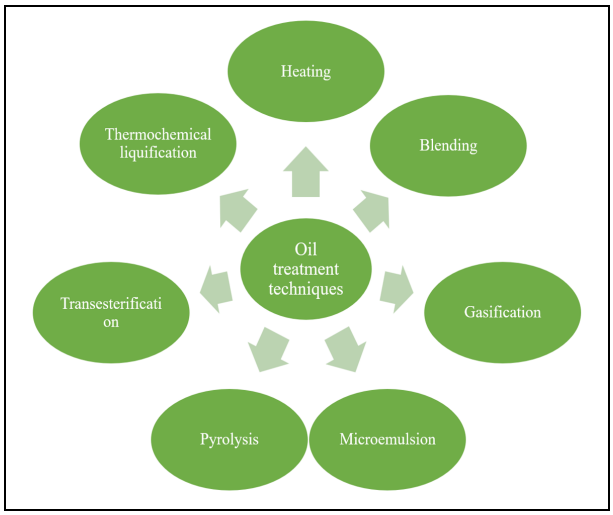


Fig. 5: Biodiesel production methods

For the ternary system, data on liquid-liquid balance, tie-lines, and phase restrictions were examined. Canola oil was converted to ethanol, glycerol, and biodiesel at temperatures between 302 K and 334 K to address ethanol phase equilibrium. The alkaline transesterification of camelina oil was optimized using an experimental approach, achieving a 98.4% fatty acid methyl ester yield. Biodiesel from jatropha was produced with a SiO_2-HF solid catalyst, converting 96% of free fatty acids. Marine macroalgae produced 1.6–11.5% biodiesel, and moringa fatty acids were transesterified using an alkaline method, yielding over 82% (Kafuku and Mbarawa, 2010).

Preheating crude palm oil at 92°C revealed that it has lower viscosity than diesel fuel. Transesterifying methanol with NaOH produced peanut methyl esters, achieving 89% yield. Another study used sodium methoxide to transesterify sunflower oil, while potassium hydroxide converted thuma oil to biodiesel, reaching 97.8% ester conversion with 0.75% KOH. Research on rice bran oil also used KOH, enhancing pomace oil with synthetic manganese for an 80% maximum yield. *Putranjiva roxburghii* non-edible oil was blended with 30% regular diesel to produce biodiesel (Haldar *et al*. 2009).

6 PROPERTIES OF BIODIESEL

The economics and profitability of biodiesel production depend on its characteristics, influenced by the fatty acid profile. Biodiesel quality is compared to standards like ASTM D6751 and EN 14214. Vegetable oils, methyl esters, and ethyl esters can be classified based on physical, chemical, and thermal properties. The main physical properties include viscosity, density, cloud point, pour point, flash point, boiling range, and freezing point. Chemical properties involve structure, ash and sulfur content, acid value, saponification value, iodine value, peroxide value, hydroxyl value, and sulfur and copper content. Thermal properties include distillation temperature, thermal degradation point, carbon residue, specific heat, and thermal conductivity (Demirbas 2007). High viscosity of these oils is a result of their high molecular weight. Vegetable oil has a flash point between 158 and 318 °C. On the other hand, the heating values fall between 39 and 40 MJ/kg. Vegetable oil's heating value is reduced by around 10% when chemically bonded oxygen is present. The number of triglycerides, free fatty acids, and carbon chains in the vegetable oils may potentially play a role in this discrepancy.

According to various studies, characterising biodiesel and its blends with diesel revealed that nearly all of the important characteristics of biodiesel and its blends are in exceptionally close connection with diesel. This makes it a potential fuel for use in compression ignition engines. An effective replacement for diesel fuels is produced under ideal conditions such as relative density, viscosity, flash point, cloud and pour points. The produced bio-diesel has the best attributes as specified by the ASTM requirements, as shown by its high energy value, fatty acid levels, and quality compound analysis (Gogoi and Baruah, 2011). As the amount of unsaturated fatty acids in biodiesel increases, so does its density (Silitonga *et al*. 2013).

The amount of unsaturation in the fatty acids is indicated by the iodine value. The quantity of iodine required to iodize the double bond found in the FAME (Atabani *et al*. 2013). The cetane number affects the biodiesel's ignition delay and combustion quality; a greater cetane number causes a shorter ignition delay. The cetane number, which is defined by the chemical structure, is influenced by the degree of unsaturation and the length of the fatty acid chain. Better cold start properties and less white smoke production are provided by high cetane numbers. The tendency to knock and the emission of particulate matter increase with a lower cetane number (Ong *et al*. 2013).

Another crucial biodiesel characteristic that defines the ability of fuel flow is viscosity. It is directly correlated with the unsaturation level of fatty acid profile. It becomes more viscous due to the bigger molecules, such as triglycerides. Incomplete combustion results from the interference of high viscosity with fuel atomization (Atabani *et al*. 2013). One of the problems with biodiesel is that it has stronger cold flow characteristics, such as cloud and pour point. Since saturated esters crystallise more easily at higher temperatures, saturated fatty acids frequently have higher melting points than unsaturated fatty acids. However, additives are added to the fuel to enhance its cold flow characteristics (Imahara *et al*. 2006). For storage and distribution, a fuel's oxidative stability is crucial since oxidation causes fuel breakdown. Higher heating value (HHV) or heat of combustion, which is the quantity of heat emitted during the whole combustion of a unit measure of fuel under standard atmospheric circumstances (101 kPa, 25°C), is used to determine the heating system value of a fuel (Sivaramakrishnan and Ravikumar 2014). The energy value of the fuel improves with an increase in the length of the fatty acid chain while decreasing with an increase in unsaturation. Biodiesel naturally contains oxygen, which improves combustion but lowers calorific value. Biodiesel is safe and have greater fire and flash point than gasoline and a boiling point of about 350°C.

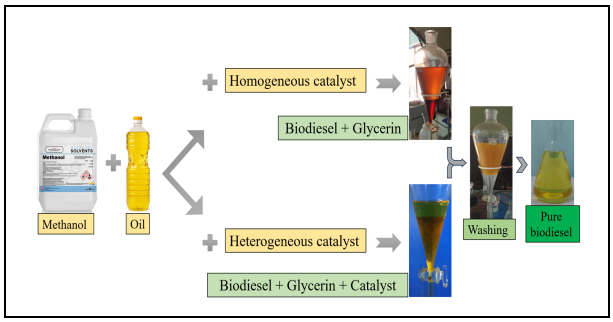


Fig. 6: Influence of catalyst in biodiesel production

6.1 Influence of Catalyst in Biodiesel Production

Fatty acid methyl esters are the primary components of biodiesel, formed by combining long-chain fatty acids with lower alkyl esters. They can be produced *via* esterification of fatty acids or transesterification with lower alcohols. Notably, transesterification can occur without catalysts but requires high temperatures, pressures, and long reaction times, increasing production costs. Despite high purity, FAME is often not considered industrial biodiesel due to these expenses. The process employs three types of catalysts: alkaline, acidic, and enzyme (Thangaraj *et al*. 2019). Fig. 6 shows the different catalyst used in the biodiesel conversion with byproducts.

6.1.1 Alkaline Catalyst

Alkaline catalysts, such as NaOH, KOH, and alkaline metal carbonates, are commonly used in biodiesel production. They offer high ester yields under moderate conditions and short reaction times (Yan *et al*.

2014). However, they are sensitive and work best with oils low in free fatty acids (FFAs), as higher FFA levels produce soap instead of biodiesel. This soap slows the separation of glycerin, biodiesel, and water. To achieve high ester yields, de-acidification of the vegetable oil is necessary before transesterification.

6.1.2 Acidic Catalyst

Acidic catalysts are more effective than alkaline ones for esterifying free fatty acids (FFAs). The acid-catalyzed transesterification process requires high temperatures (about 100 ℃), around 5 bars of pressure, and a large volume of alcohol, proceeding more slowly than alkaline catalysis. These catalysts are particularly useful for feed oils with high acid values. Solid acid catalysts have gained attention for their ability to achieve up to 90% conversion through simultaneous esterification and transesterification. However, commercial viability remains a challenge due to issues like corrosion and side product formation, which increase biodiesel production costs. The primary advantage of acidic catalytic conversion is its effective esterification of FFAs in high-acid-value waste oils.

6.1.3 Enzymes

Enzymes, particularly lipases from various microorganisms, are used as catalysts in biodiesel production. By maintaining moderate temperature, pressure, and pH, biocatalysts enable higher conversion rates and produce high-quality glycerol with minimal residue or soap, unlike alkali or acid catalysts. They can be used with feedstocks that have high acid values. However, the major drawbacks include the need for high enzyme concentrations, lengthy reaction times, and challenges in separating the enzyme from the final product, which increases production costs.

6.1.4 Homogeneous Catalyst

In biodiesel production, both acidic and basic homogeneous catalysts are commonly used, with acid catalysts generally being less active than base catalysts. However, acid catalysts become more efficient when free fatty acids (FFA) exceed 1%. They also help prevent foaming and facilitate the esterification of FFAs into fatty acid methyl esters (FAME), enhancing biodiesel production. The acid-catalyzed process is slower, requiring high temperature and pressure. Deep eutectic solvents (DESs) have been explored for biodiesel production, showing over 90% conversion rates.

A detailed discussion on DESs and their effectiveness is provided in Section 8. For alkaline catalysts, high-quality FFAs are essential, as soap formation can limit reactions and biodiesel yield. Research indicates that alkali-catalyzed transesterification is successful when FFA levels are below 1% and moisture is minimal. Table 1 highlights the differences and similarities between homogeneous and heterogeneous catalysts.

A higher ester conversion can be achieved at relatively low temperatures and pressures, reducing process costs. Alkaline metal hydroxides like KOH and NaOH react faster than sodium and potassium methoxide, though they are less cost-efficient. However, increasing catalyst concentration to 1-2% makes them a viable option for converting vegetable oil. Hydroxide reactions with alcohol can produce water in an anhydrous oil-alcohol mix. Tables 2 and 3 compare key parameters and list various homogeneous base and acid catalysts from scientific studies.

Table1. Compare homogeneous and heterogeneous catalyst

Properties	Heterogeneous Catalysts	Homogeneous Catalysts
Rate of Reaction	Reasonable conversion rate	High speed conversion rate
Catalyst Reuse	Can be reused	Cannot reuse
After Treatment	Recoverable	There should be no neutralization of catalyst recovery and no use of waste chemicals
Methodology	Continuous fixed-bed operation	Continuous process is limited
Presence of H_2O/ Free Fatty Acids	Not a sensitive process	Very Sensitive

Table 2. List of biodiesel production from various oils using homogeneous base catalysts

Source	Catalyst Used	Alcohol/Oil Ratio, Temp. (℃)/ Time (h)	Yield %
Sunflower Oil	NaOH	6:1, 60/1	97
Cottonseed Oil	TMAH	6:1, 64/2	98
Waste frying Oil	$NaOCH_3$	6:1, 60/1	93
Waste frying Oil	TMG	12:1, 65/1.5	93.82
Cottonseed Oil	TEA	9:1, 190/3	55
Waste frying Oil	BTMAH	6:1, 65/2.5	95
Madhuca longifolia oil	KOH	1:0.35, 60/0.5	90
Castor Oil	KOH	5.4:1, 64/2.5)	97.82
Waste Cooking Oil	KOH	9.4:1, 62.4/2	98.26
E. angustifolia L seed oil	KOH	9:1, 60/1	95
Citrullus vulgaris seed oil	NaOH	5:1	70

6.2 Heterogeneous Catalyst

Heterogeneous catalysts reduce processing costs associated with homogeneous catalysis and limit

pollutant formation. They enable rapid recycling and reuse, making the process more environmentally friendly and cost-effective. Heterogeneous catalysts can handle high levels of free fatty acids and moisture, making them essential in biodiesel synthesis under extreme conditions like high temperature and pressure. They can be recovered from reaction mixtures, withstand aqueous treatments, and be tailored for high activity and selectivity. These catalysts allow for the grafting and trapping of active molecules on solid supports like silica or alumina. Various compounds, including alkali earth metal oxides and ion exchange resins, are used in reactions such as condensation, isomerization, oxidation, and transesterification.

Table 3. List of biodiesel production from various oils using homogeneous acid catalysts

Source	Catalyst Used	Alcohol/Oil Ratio, Temp.(°C)/ Time (h)	Yield%
Sunflower Oil + Oleic Acid	H_2SO_4	6.12:1, 55/4	96
Soyabean Oil	$C_2HF_3O_2$	20:1, 80/6	98
Canola Oil	$AlCl_3$	1:1 24:1, 115/18	98
Neem Oil	H_2SO_4	6:1	83

Table 4. List of biodiesel production from various oils using heterogeneous base catalysts

Source	Catalyst used	Alcohol /Oil Ratio, Temp.(°C)/ Time (h)	Yield %
Soyabean Oil	$Sr_3Al_2O_6$	25:1, 60/1	96
Sunflower Oil	$CaZn(OH)_4$	20:1, 78/3	95
Soybean oil	K/Al_2O_3-Monolith	32:1, 120/6	60
Microalgae oil	CaO/dolomite catalyst	6:1, 65/3	90
Cottonseed Oil	KOH–CaO	7:1	96.44
Waste Cooking Oil	Carbon extracted from date seed modified with Ca and Mg oxides	15:1, 65/1.5	94.27
Waste cooking oil	Hybrid CaO/Al_2O_3 aerogels 3:1, CaO/Al_2O_3	1:1, 65/4	89.9
Castor oil	Carbon-based magnesium oxide (MgO)	12:1, 75/1	96.5

Strontium oxide has a high basicity, and because of its solubility, it does not solubilize in methanol; hence, it maintains up to 10 cycles of efficiency. When compared to solid base catalysts, the catalytic activity of solid acid catalysts is significantly lower. CaO, MgO, SrO, KNO_3/Al_2O_3, K_2CO_3/Al_2O_3, KF/Al_2O_3, Li/CaO, KF/ZnO, Mg/Al, and zeolites of Lithuanian and Alpine provenance are some of the various solid base catalysts that can be used for transesterification. At ideal reaction circumstances, these catalysts have a yield of biodiesel that is greater than 92% (Kim *et al*. 2004).

Research by Farooq and coworkers highlights the potential of low-cost solid wastes as catalysts for efficient biodiesel synthesis. Calcining eggshells at 900°C converts calcium carbonate into calcium oxide, achieving up to 93.5% biodiesel yield during transesterification. Utilizing waste materials addresses disposal challenges while adding value to various processes. Solid catalysts have also been developed from organic waste, such as plantain peels, wood, and palm. For instance, using banana peels as a catalyst can produce potassium and sodium oxides. To create the banana peel catalyst, peels are dried at 80 °C for 48 hours and then calcined at 700 °C for four hours. Tables 4 and 5 summarize key reaction parameters for various heterogeneous catalysts.

Table 5. List of biodiesel production from various oils using heterogeneous acid catalysts

Source	Catalyst Used	Alcohol /Oil Ratio, Tempe. (°C)/ Time (h)	Yield%
Oleic acid	HZSM-5 Zeolite	20:1, 100/7	81
Waste frying Oil	Fe $(HSO_4)_3$	15:1, 205/4	95
Soybean Oil	30% $WO_3/AlPO_4$	30:1, 180/5	73
Palmitic acid	Sulfonated carbon nano-horn	33:1, 65/5	93
Polanga Oil	Sulfonated Carbon	30:1, 180/5	98.5
Oleic acid	Sulfated LaO/HZSM-5	5:1, 100/7	99.8
Microalgal Oil	Spirulina platensis. β-Strontium silicate (β-Sr_2SiO_4).	12:1 65/2	76.34

6.3 Influence of Process Parameters in Biodiesel Production

6.3.1 Water Content

Felizardo *et al*. (2007) found that water in feedstock accelerates hydrolysis while reducing ester formation. For acid-catalyzed reactions, water content must be below 0.5% to achieve a 90% biodiesel yield (Bogalhos *et al*. 2012). Water produced as a byproduct in acid-catalyzed biodiesel synthesis hinders the reaction and decreases engine performance. Moisture removal typically involves anhydrous sodium sulfate (Na_2SO_4) or magnesium sulfate. Preheating oil to 120 °C can eliminate water. Some enzymes require water, but if the water content is too low, enzyme activity is affected (Norjannah *et al*. 2016)

6.3.2 Methanol to Oil Ratio

According to IS IK (2021), producing one mole of alkyl ester requires three moles of alcohol and one mole of triglyceride. Following Le Chatelier's principle,

increasing reactant concentration accelerates product formation, so a higher alcohol-to-oil ratio enhances production. However, recovering glycerol and unreacted methanol can be difficult due to emulsion formation during saponification. Biodiesel production results in two phases: the top phase consists of biodiesel, while the lower phase contains crude glycerol, which includes alcohol, glycerol, water, soaps, and other organic materials (Rodrigues *et al*. 2017).

The composition of these components varies with feedstock quality. The post-treatment of crude glycerol typically involves three stages: (1) neutralization to remove soaps and salts, (2) vacuum evaporation to eliminate methanol and water, and (3) refining to enhance glycerol quality. These processes increase the overall cost of biodiesel. A study using methanol and NaOH as catalysts for waste sunflower oil transesterification found that a 6:1 alcohol-to-oil ratio achieved a maximum conversion of 99%. In contrast, transesterification of waste canola oil with a 1:1 methanol-to-oil ratio yielded only 49.5% (Binhweel *et al*. 2021).

6.3.3 Catalyst Concentration

Without a catalyst, converting oil or fat to biofuel requires temperatures above 100 °C (Chakraborty *et al*. 2011). Higher catalyst concentrations generally increase product yield by speeding up the reaction rate. However, increased catalyst concentration can raise the mixture's viscosity, leading to decreased conversion. Studies have shown that a 1.5% concentration of copper vanadium phosphate is optimal for producing soybean oil biodiesel. While more enzymes can accelerate conversion, excessive enzyme concentration may cause agglomeration, reducing active sites. Research on CaO and ZrO_2 as heterogeneous catalysts indicates that a higher Ca/Zr ratio improves yield but compromises catalyst stability. Thus, optimal catalyst concentration varies by type and raw material.

6.3.4 Stirring Speed

Proper mixing of reactants is crucial for successful transesterification and enhanced FAME synthesis (Chakraborty *et al*. 2011). Agitation increases particle collision rates and diffusion, leading to shorter reaction times and higher conversion rates. However, after a certain stirrer speed, product yield plateaus. The optimal stirring speed varies by feedstock due to differing physical properties. Stirring ensures reactants reach the catalyst surface, which is essential for porous and enzyme catalysts (Madhu *et al*. 2016). While conversion rates improved from 100 to 200 rpm, there was little improvement at 250 rpm due to enzyme shearing effects. Thus, 200 rpm is optimal for biodiesel production using enzyme reactions.

6.3.5 Reaction Temperature

Temperature significantly affects the transesterification reaction; higher temperatures increase both reaction rates and product yields. Biodiesel viscosity rises when temperatures drop below 50 °C. For used cooking oil, the oil is heated to 120 °C, then cooled to 60 °C (Daramola *et al*. 2016). For enzyme reactions, conversion rates improve between 30–55 °C, with the highest conversion for jatropha oil at 55 °C and cottonseed oil at 50 °C. Research showed no significant difference in conversion between 45 and 60 °C. At 32 °C, conversion was slightly lower than at 45 and 60 °C, but improved after 4 hours compared to those temperatures.

6.3.6 Reaction Time

Increasing reaction time can achieve up to 99% conversion of starting material. The availability of reactants in the medium also impacts conversion rates. If reaction parameters are not properly adjusted, the reaction may reverse, lowering conversion. Lipase-catalyzed processes can take between 7 to 48 hours. Research indicates that longer reaction times reduce the specific gravity of the product exponentially, reaching an asymptotic value. For instance, a conversion of 96.10% is achieved at 1 hour, with minimal difference at 3 hours (96.35%). Optimizing reaction time is crucial for reducing production costs (Silitonga *et al*. 2017).

7. DIESEL ENGINE

Diesel engines operate on the principle of compression ignition, where air is compressed in the cylinder to increase temperature and pressure, allowing for instant ignition of the fuel when injected. For efficient combustion, the fuel spray must be evenly distributed to mix with the hot air in the chamber. Diesel engines typically use high compression ratios of 12 to 24, leading to automatic ignition of the fuel-air mixture. The combustion process consists of three main steps.

7.1 Ignition Delay

The combustion process includes a crucial preparation phase where fuel has entered the combustion chamber but ignition has not yet occurred. This period, known as the start of combustion (SOC), lasts from fuel injection to when the pressure-time curve diverges from the driving curve. Diesel engine delay time significantly affects performance and design, with variations observed between diesel and biodiesel (Gumus, 2010). During this delay, fuel is heated to its self-ignition temperature, atomized, evaporated, and mixed with air. Low-viscosity fuels experience a shorter physical delay, while higher viscosities result in longer delays, influenced by ambient temperature. Chemical reactions gradually accelerate during this time, leading up to ignition, with physical

delays typically shorter than chemical delays, although higher temperatures can extend physical delays relative to chemical ones.

7.2 Rapid Combustion

During this phase, a portion of the premixed charge that was injected into the cylinder during the ID phase starts to burn. The pressure has suddenly increased. Both the volume of fuel in the combustion chamber and the length of the ID has an impact on how quickly and how much pressure is raised.

7.3 Controlled Combustion

The combustion behaviour is primarily controlled by the rate at which fuel is continuously delivered into the cylinder while hot compressed air is present. The in-cylinder mixture rapidly cools as the piston retract, drastically slowing the pace of chemical reactions. The system may be in a condition that is far from chemical equilibrium when the reaction rates are so low that the word "frozen" is frequently used to describe them. One example of a chemical product that has essentially "frozen" above its equilibrium level is a region with high NO_x levels (Ban-Weiss *et al*. 2007)

8. ENGINE PERFORMANCE FOR DIFFERENT OIL BIODIESEL

8.1 Palm Oil Biodiesel

Engine performance was tested using neat palm oil methyl ester (B100), B50, and neat diesel (B0) under various speeds and loads. Results showed that palm oil methyl ester has a higher specific fuel consumption (SFC) due to its lower energy content compared to diesel. However, B100 reduced tailpipe emissions of NO, UHC, and smoke opacity by 5.0%, 26.2%, and 66.7%, respectively, due to improved combustion and a higher cetane number. The PME content had minimal effect on CO emissions, with B50 showing a decrease of 0.89%. Despite its higher SFC, PME is technically feasible as an alternative to fossil diesel for light-duty diesel engines, both in neat and blended forms.

An indirect ignition diesel engine running on 5% palm oil (P5) and 5% coconut oil (C5) at 85% throttle showed favorable emissions and performance. P5 and C5 had 1.2% and 0.7% lower brake power compared to B0 due to lower heating values. P5 increased exhaust gas temperature by 1.42%, while C5 decreased it by 1.58%. CO emissions were reduced by 7.3% and 21% for C5 and P5, respectively, while HC emissions decreased by 23% and 17%. C5 reduced NO_x emissions by 1%, while P5 increased them by 2%. Additionally, studies on 5%, 20%, and 40% blends of palm biodiesel and diesel in a Euro 3 light-duty car showed that biodiesel increases NOx emissions, particularly with B20, which rose by 13.7% and 23.2% in the NEDC and ADC, respectively. CO emissions also increased, with the highest rises observed in B20 and B40 during the NEDC and ADC.

8.2 Rapeseed Oil Biodiesel

It was investigated that the impact of canola oil biodiesel and its blend on the emission and enactment of a low heat loss engine under coating and uncoated conditions. When the author learned that the biodiesel has a gain in power of between 1.6% to 3.5% as opposed to 8.4%. As opposed to 4.9% for, the drop in SFC for biodiesel is between 4.7% and 8%. Both smoke (4.7-8.2%) and CO (22–24%) exhaust gas emissions are significantly lower than for diesel. However, compared to diesel, NO_x emissions rise by 4.8% to 7.3%. This is explained by the ceramic's increased after-combustion temperature and higher oxygen concentrations. While it rises by 11.4% for diesel, the temperature of the exhaust gas rises by between 5.5% and 2.7% for biodiesel.

A study on clean rapeseed biodiesel and mixtures of 5%, 20%, and 70% at full load showed that B5 produced similar engine power output to diesel, while higher blends yielded lower power. Biodiesel resulted in higher BSFC, higher exhaust gas temperatures, and lower CO and smoke opacity, with reduced NO_x emissions. B20 provided the best brake thermal efficiency, indicating its potential for certification in unaltered diesel engines due to its performance and environmentally friendly emissions.

8.3 Soybean Oil Biodiesel

Fontaras *et al*. (2009) studied the effects of soybean oil biodiesel and a 50% blend (B50) on a Euro 2 diesel passenger car. The results indicated that biodiesel increased specific fuel consumption (SFC) by 9% in the NEDC and 4.5% in the Artemis cycles due to its lower energy content. B50 and B100 led to increases in CO emissions of 54% and 95%, respectively, and HC emissions of 31% and 58%. While NO_x emissions were similar or slightly lower with B50 compared to diesel, B100 caused a 6-9% increase. Biodiesel reduced solid particle count but increased total particle numbers. The authors concluded that high biodiesel blends can significantly affect emissions based on driving conditions and blending ratios, but emphasized the need for further research. The combustion and performance characteristics of a direct injection engine powered by biodiesel from soybean oil and its blends (B0, B30, B50, B80, B100) were studied. Results showed a slight increase in brake specific fuel consumption (BSFC) due to biodiesel's lower heating value. Brake thermal efficiency (BTE) was marginally lower for biodiesel blends at low and high engine loads. However, CO and smoke emissions decreased significantly at high loads, while hydrocarbon (HC) emissions were comparable to diesel. Nitrogen oxides (NO_x) were slightly higher with

biodiesel blends, attributed to increased oxygen levels raising combustion chamber temperatures. The study concluded that biodiesel's extra oxygen positively impacts engine performance and could serve as a partial or complete diesel replacement.

To assess the effect of alternative fuel on engine emissions, three different types of fuel were used: pure soybean methyl-ester biodiesel fuel, ultra-low sulphur diesel fuel (BP15), and (B100), as well as a synthetic Fischer-Tropsch fuel. The BSFC for B100 is around 15% higher than for BP15, despite the fact that the brake efficiency is about 8% lower for B100. B100 emits NOx at a rate that is around 16.7% lower than BP15. HC emissions for B100 are around 12% lower than for BP15 but higher than for BP15 while CO emissions are roughly the same for both (FT). The most likely cause of the increase in PM mass emissions is unburned or only partially burned hydrocarbon (HC) emissions.

8.4 Sunflower Oil Biodiesel

A 4-cylinder, direct-injection, 4-stroke turbodiesel engine's emission characteristics were examined when it was operating at different speeds and at full load. The outcome demonstrated that, at all engine speeds, diesel fuel generally produces lower smoke HC and CO emissions than sunflower oil methyl ester. By improving the combustion quality, the test engine's turbocharger mechanism and biodiesel fuel's oxygen concentration have reduced emission values. The authors came to the conclusion that because biodiesel has lower exhaust emissions than diesel fuels, it has a better impact on air quality.

8.5 Jatropha Oil

On an unmodified diesel engine, evaluation of the performance and exhaust emissions of blends of 5%, 10%, 20%, and 30% jatropha biodiesel with diesel fuel was done (Chauhan *et al*. 2012). In the experimental results indicate that diesel fuel and its mixes performed similarly in engines when using jatropha biodiesel. All fuel blends had greater BSFC and NO_x than diesel, but worse brake thermal efficiency, HC, CO, CO_2, and smoke density. According to the authors, it can be utilised in a typical diesel engine without needing to be modified. There are, however, some factors that can be evaluated in the future, such as the prediction of the appropriate mix with respect to the various engine parameters by adjusting the fuel spray time with common-rail fuel injection.

8.6 Mahua Oil Biodiesel

A diesel engine's efficiency and emissions were studied using Madhuca indica biodiesel as fuel. A single-cylinder, four-stroke, air-cooled, direct-injection engine with compression ignition was tested aboard Mahua. utilising oil methyl ester with diesel as fuel. Due to the lower heating value and higher viscosity of biodiesel fuel, the results showed that at full load, power loss with mahua oil methyl ester was roughly 13% with a 20% rise in fuel consumption. Because to the higher oxygen concentrations that promoted combustion, mahua ester produced emissions such as carbon monoxide and hydrocarbons that were 26% and 20% lower than those from diesel, respectively. Due to the decreased cylinder temperature, nitrogen oxides in the ester were 4% lower than in diesel.

8.7 Tobacco Oil Biodiesel

The performance and exhaust emissions of a turbocharged indirect injection diesel engine were evaluated utilising 10%, 17.5%, and 25% of a mixture of tobacco seed oil methyl ester. The author discovered that the engine's torque and power were unaffected by the addition of up to 25% more TSOME volume. Despite the TSOME's heating value being 10.8% lower than that of diesel fuel. It was also demonstrated that adding tobacco seed oil methyl ester to diesel fuel decreased CO and SO_2 emissions since TSOME has a low sulphur content, but marginally increased NO emissions because of a higher combustion temperature. This is because TSOME has an oxygen content of about 11.4% by weight.

8.8 Rubber Oil Biodiesel

A study on a diesel engine running on rubber seed oil methyl esters showed that B10 achieved a brake thermal efficiency of 28%, higher than diesel's 25%. Lower biodiesel percentages in blends resulted in reduced fuel consumption at all loads compared to diesel. Carbon monoxide emissions were lower with biodiesel blends, while higher biodiesel concentrations led to increased NO_x and CO_2 emissions. Smoke emissions were generally lower with biodiesel blends. The study concluded that biodiesel from raw rubber seed oil is a viable alternative to diesel in compression ignition engines. A single-cylinder diesel engine's performance, emission, and combustion traits were reported, along with those of its biodiesel mixes (B20, B60, and B80) with regular diesel. They discovered that compared to diesel, biodiesel blends had lower brake thermal efficiency. For biodiesel, longer combustion times and slower heat release rates were also observed.

8.9 Desert Dates Oil Biodiesel

The performance and emission characteristics of a diesel engine running on B100 (100% desert date biodiesel) and B5 (5% mix) were studied and B0 (0% biodiesel) at various rpm (1200–2200). Using plain biodiesel instead of diesel resulted in a slight 2% reduction in fuel use. The engine's power output was

decreased by about 4% when utilising B100 in comparison to diesel. While using neat Desert date biodiesel instead of diesel, the emission of nitric oxide was reduced by roughly 6%. It has been shown that the 5% blend lowers NO even more. Biodiesel has a 60% and 68% reduction in CO and HC emissions when compared to diesel, respectively.

8.10 Jojoba Oil Biodiesel

A study on a two-cylinder diesel engine using jojoba methyl ester (JME) showed that JME had slightly higher thermal efficiency and 8.2-9.8% lower BSFC compared to diesel. JME produced 14-16% more NO_x at lower speeds but had lower CO emissions. HC emissions were similar at high speeds. Exhaust gas recirculation (EGR) reduced NOx emissions as the rate increased, with EGR levels of 5-15% balancing HC, CO, and NO_x emissions at a minor economic cost (Saleh 2009).

8.11 Rice Bran Oil Biodiesel

The viability of rice bran oil methyl ester (CRBME) in engines was investigated. The outcome demonstrated that the brake thermal efficiency only falls with CRBME blend slightly as a result of the methyl ester's reduced heating value. Additionally, due to the increased oxygen levels of methyl ester, a considerable decrease in CO, UBHC, and particle pollution was seen with only a slight increase in NO_x emission compared to diesel.

8.12 Neem Oil Biodiesel

The emission characteristics of a four-stroke naturally aspirated (NA) direct injection (DI) diesel engine was investigated using the methyl ester of neem oil (NOME). They discovered that employing biodiesel-diesel mixes as opposed to diesel resulted in higher NO_x emissions but decreased carbon monoxide (CO) and smoke emissions. The increased oxygen concentrations in biodiesel are the cause of the reduction in all emissions. Yet, compared to pure diesel, NO_x emissions from diesel-biodiesel mixes were somewhat reduced when EGR was utilised. The emissions and performance of a direct injection diesel engine were investigated using neem oil and diesel. They discovered that neem biodiesel has a slightly lower brake thermal efficiency (BTE) at all loads and diesel has slightly higher brake specific fuel consumption (BSFC). The amount of NO_x, smoke density, CO, and unburned hydrocarbon (UHC) emissions was significantly reduced when compared to diesel fuel.

8.13 Apricot Oil Biodiesel

The performance and emissions of a diesel engine were evaluated using apricot seed kernel oil methyl ester (ASKOME) and its blends. Lower blends (B5, B20) improved engine power but slightly increased emissions. Higher blends (B50) and pure ASKOME effectively reduced CO, HC, and smoke density due to better combustion from higher oxygen content but resulted in lower performance and slightly increased NOx. Thus, adding small amounts of ASKOME can improve diesel performance and reduce emissions.

8.14 Pistacia Bunge Oil Biodiesel

Investigations were conducted into the emission characteristics of a diesel engine using a biodiesel blend made from Pistacia chinensis Bunge seed (Zhihao *et al*. 2011). Due to the greater oxygen concentrations and lack of sulphur in the mix, the result indicated that CO, HC, and exhaust smoke emissions drop as the fraction of biodiesel in the blend increases. Because of the higher oxygen levels in B30, which also raises the in-cylinder temperature, the NO_x emissions are somewhat enhanced when the engine is working with B30.

8.15 Sal Oil Biodiesel

Vedaraman *et al*. (2012) investigated the efficiency and emissions of a diesel engine powered by sal oil methyl ester. When compared to diesel fuel, biodiesel fuel reduces exhaust emissions such CO (45%), HC (55%) and NOx (12%) due to its higher oxygen content, higher cetane number, and lack of sulphur. Sal oil methyl ester emits more CO_2 than diesel, in comparison. This is because fuel based on esters burns more efficiently than diesel. Also, they found that there is no appreciable difference in brake thermal efficiency between diesel fuel and biodiesel. However, it has a higher BSFC than diesel fuel. However, they came to the conclusion that using biodiesel made from sal oil in a diesel engine doesn't require any modifications.

8.16 Waste Cooking Oil Biodiesel

Mumtaz *et al*. (2012) investigated diesel engine emission utilising WCOB at volumetric blends of 5%, 20%, 40%, 50%, and 80%. Their study's key conclusions showed that, on average, CO emissions decreased from 7.3% for WCOB-5 to 62.82% for WCOB-100. The average reduction for PM increased from 3.16 percent for WCOB-5 to 54.3 percent for WCOB-100. But it was found that NOx increased, going from 1.68 percent for WCOB-5 to 4.7% for WCOB-100. The authors came to the conclusion that WCOB-20 was a useful WCOB blend that reduced CO, PM, and NO_x emissions reasonably.

9. IMPROVING COMBUSTION PERFORMANCE

Despite biodiesel's benefits, its density and viscosity after transesterification remain higher than diesel, affecting processes like atomization and fuel-air mixing. In ROME biodiesel, a turbocharger reduced these issues by increasing air pressure and temperature, improving brake power and combustion, but also

increasing NO_x emissions. For Jojoba Methyl Ester (JME), viscosity was reduced by heating the fuel and adding diethyl ether, though the additive negatively impacted ignition delay. Preheating JME to 50°C and 70°Creduced ignition delay, and peroxidation further lowered high viscosity. Low Heat Rejection (LHR) engines, with thermal barrier coatings, improve fuel efficiency and exhaust energy recovery, making biodiesel use more effective without preheating (Haşimoğlu *et al*. 2008). Preheating biodiesel (cottonseed oil methyl ester) to 90°Cimproved Brake Thermal Efficiency (BTE) and reduced CO emissions, but higher temperatures (120°C) decreased brake power due to fuel leakage from reduced viscosity.

10. BIODIESELS ON EMISSION BEHAVIOUR

Biodiesel improves engine combustion and increases NO_x emissions due to its oxygen content, fuel chemistry, and injection timing. Olive oil methyl ester reduced CO, NO_x, and CO_2 emissions compared to diesel. Biodiesel's 11% oxygen content leads to more complete combustion, lowering HC emissions, though it increases BSFC and NO_x. NO_x emissions can be reduced by lowering in-cylinder temperatures, often achieved through an EGR system (Dorado 2003). Studies with various biodiesels showed that higher EGR levels reduced NO_x and soot emissions by lowering oxygen and flame temperature (Tsolakis *et al*. 2007). Biodiesel's lower soot production is due to its oxygenated nature.

In conclusion, biodiesel from non-edible oils like Jatropha and Camelina shows promise as a sustainable alternative to fossil fuels, with environmental benefits despite challenges in production and engine compatibility. Continued research is essential to enhance biodiesel technology and realize its full potential in reducing greenhouse gas emissions.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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