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Utilizing Waste Cooking Oil for Sustainable Biodiesel Production: A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

ABSTRACT

The environmental and economic challenges posed by the over-reliance on fossil fuels have driven the search for alternative and sustainable energy sources. Waste cooking oil (WCO) presents a viable feedstock for biodiesel production, offering a dual solution to waste management and renewable energy generation. This comprehensive review examines the current state of biodiesel production from waste cooking oil, exploring the benefits, challenges, and processes involved. Biodiesel derived from WCO has several environmental advantages, including lower greenhouse gas emissions, biodegradability, and enhanced engine lubricity compared to traditional fossil fuels. Moreover, utilizing it for biodiesel addresses waste disposal issues, reducing the contamination of land and water resources. Despite these benefits, several challenges remain, such as the variability in its composition, contamination, and the need for efficient purification and transesterification processes. The review explores various methods for converting WCO into biodiesel, highlighting the

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key stages of the transesterification process, including the use of catalysts, alcohols, and reaction conditions. Additionally, advanced techniques such as ultrasound-assisted and microwave-assisted transesterification are discussed for their potential to increase efficiency and reduce processing time. This paper also addresses the sustainability aspects of biodiesel production from it, emphasizing its role in promoting a circular economy and reducing waste. The use of its contributes to a closed-loop system, where waste is transformed into a valuable resource. Furthermore, the review explores the economic and social impacts of biodiesel production, noting its potential to create jobs, reduce import dependence, and support local communities. In conclusion, this review underscores the significant potential of waste cooking oil in sustainable biodiesel production. It calls for continued research and technological innovation to optimize processes, enhance efficiency, and overcome existing challenges, thereby contributing to a cleaner and more sustainable energy landscape.

Keywords: Renewable; biodiesel; lubricity; purification; transesterification; sustainability; social impacts.

1. INTRODUCTION

Environmental changes resulting from high fossil fuel usage, combustion emissions, and resource depletion have spurred interest in alternative fuel sources, such as biodiesel made from waste vegetable oils and various plants, including Paratroop, castor, and sunflower [1]. The American Society for Testing and Materials defines biodiesel as “mono alkyl esters of long-chain fatty acids derived from vegetable oil or used cooking oil.” Biodiesel must also meet a greenhouse gas emissions standard, with emissions at least 50% lower than traditional fossil fuels [2]. India relies heavily on petroleum imports, producing only 30-40% of its domestic demand and importing the rest, costing approximately 10,00,000 million rupees annually. This reliance on imports could be reduced through biodiesel production [3]. The Intergovernmental Panel on Climate Change (IPCC) warns that global temperatures must be limited to 1.5°C to avoid catastrophic effects on biodiversity, with a 40% reduction in greenhouse gas emissions needed to meet this target [4-5]. Biodiesel, derived from used cooking oil, has potential as a renewable resource for fuel production. It contains free fatty acids that can be converted into esters through a transesterification process with alcohol and a suitable catalyst [6].

The combustion of fossil fuels contributes to climate change through greenhouse gas emissions, ocean acidification, and rising sea levels, all of which have harmful effects on agriculture [7]. Furthermore, petroleum refineries are significant sources of air, water, and land pollution, releasing pollutants such as nitrogen oxides (NOx), carbon monoxide (CO), sulfur dioxide, and hydrogen sulfide. These emissions pose health risks, causing cancer, asthma, and reproductive issues. Moreover, refineries often use deep wells to dispose of wastewater, leading to potential contamination of groundwater and surface water [8]. Biodiesel's growing popularity stems from its environmental benefits compared to traditional fossil fuels. Since it's made from renewable sources like plants and waste cooking oil, it offers a sustainable alternative that could help reduce dependence on non-renewable resources and mitigate environmental impacts. Production of Biofuels in Netherlands, India and USA illustrated in Fig. 1. The Netherlands emphasizes advanced biofuels and sustainability, with bio-refineries using rapeseed, corn, and waste materials. India targets energy independence, primarily producing bioethanol from sugarcane and biodiesel from jatropha and waste cooking oil, aiming for 20% ethanol blending by 2025. The USA, a global leader, uses corn for bioethanol and soybeans for biodiesel under its Renewable Fuel Standard program.

Waste cooking oil (WCO) has emerged as a valuable resource for sustainable biodiesel production, offering an effective solution to two critical environmental challenges: waste management and renewable energy generation [9]. WCO, typically discarded from domestic and industrial kitchens, contains significant amounts of free fatty acids suitable for conversion into biodiesel through the transesterification process. This transformation involves

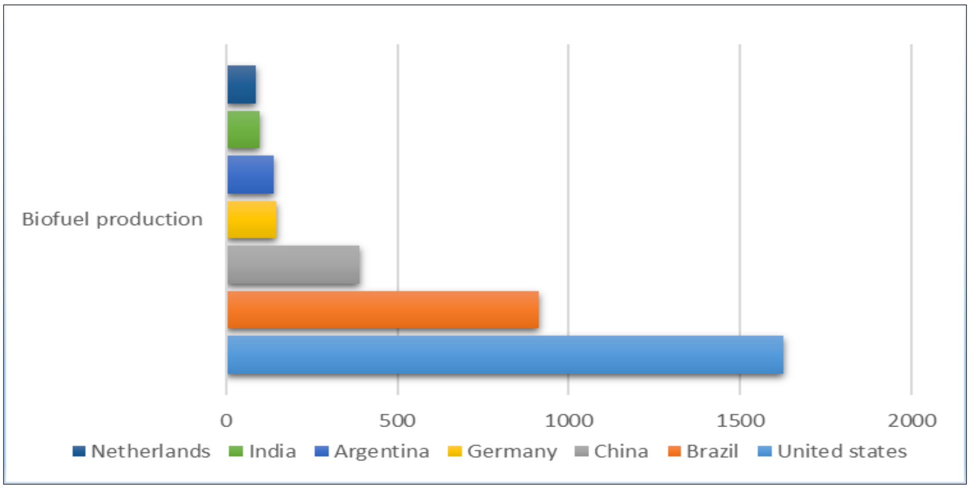

Fig. 1. Production of Biofuels in Netherlands, India and USA

the chemical reaction of triglycerides in the oil with alcohol, typically methanol or ethanol, in the presence of a catalyst such as sodium hydroxide or potassium hydroxide [10]. By repurposing WCO for biodiesel, this approach not only reduces environmental pollution but also contributes to a circular economy by transforming waste into a valuable resource. Biodiesel derived from WCO has several advantages over traditional fossil fuels, including lower greenhouse gas emissions, improved biodegradability, and enhanced engine lubricity. Furthermore, its production supports local economies by creating new business opportunities and reducing dependence on imported fossil fuels. To ensure the sustainability of biodiesel production from WCO, it is essential to address potential challenges such as feedstock variability, contamination, and process efficiency. Ongoing research aims to optimize these processes, increase yield, and promote the use of WCO as a reliable feedstock for biodiesel, thereby advancing the global transition toward greener and more sustainable energy sources [11].

2. RAW MATERIALS USED FOR MAKING BIODIESEL AND ITS PROPERTIES

Biodiesel offers several environmental advantages compared to traditional fossil fuels. Sources of Biodiesel and its properties with viscosity and pour point (Fig. 2). It has lower pollutant emissions, is biodegradable, and improves engine lubricity, contributing to sustainability [9,10]. A critical characteristic of biodiesel is its high cetane number, indicating quality fuel combustion. Biodiesel typically contains no aromatics or sulphur, and it has an oxygen content of 10-11% by weight, which contributes to lower greenhouse gas emissions [11].

2.1 There are Various Raw Materials Used to Produce Biodiesel, Including

2.1.1 Waste cooking oil

Waste cooking oil, derived from plant-based oils, is a significant resource for biodiesel production. This oil is available in large quantities worldwide, especially in developing countries, but improper disposal often leads to environmental contamination. In the United States, approximately 100 million gallons of waste cooking oil are produced daily, while the average per capita waste cooking oil is about 9 pounds [12]. In Canada, with a population of 33 million, the total waste cooking oil production is estimated at 135,000 tons annually [13], while in European countries, it is between 700,000 and 1,000,000 tons per year [14]. The high content of free fatty acids in waste cooking oil makes it a viable source for biodiesel through the transesterification process.

2.1.2 Animal tallow

Animal tallow is another source for biodiesel. In Brazil, it is the second most used raw material for biodiesel production after soy oil [15]. Tallow contains significant saturated and unsaturated fatty acids, with 26% palmitic acid, 14% stearic acid, and 47% oleic acid.

2.1.3 Algae oil

Algae is a promising source for biodiesel due to its high lipid content, with microalgae having 40-80% lipid by dry weight [16]. This source requires less land and can be grown in natural or artificial environments, using light, carbon dioxide, and nutrients for growth. The fatty acids in algae oil include 14.6% palmitic acid, 26.9% oleic acid, and 22.8% linoleic acid [17].

2.2 Biodiesel Can Also be Derived from Various Plant Oils

2.2.1 Cotton seed oil

This oil has high levels of unsaturated fatty acids, with 70% unsaturated, including 18% monounsaturated and 52% polyunsaturated fatty acids [17].

2.2.2 Sunflower oil

Known for its high linoleic acid content, sunflower oil can be extracted mechanically or chemically. About 85% of its fatty acids are unsaturated, with oleic and linoleic acids making up 43% and 47%, respectively [18].

2.2.3 Palm oil

Palm biodiesel has a cetane number ranging from 42 to 62, surpassing the minimum requirement of 51 [19]. Its high cetane number indicates a quality source for biodiesel.

2.2.4 Jatropha oil

Jatropha curcas seeds contain 27-40% oil, with high oleic, linoleic, palmitic, and stearic acid content, making it a strong candidate for biodiesel production [20].

2.2.5 Neem oil

Neem seeds contain 20-30% oil, primarily unsaturated fatty acids, making it suitable for biodiesel [21].

Overall, biodiesel derived from these various raw materials offers an environmentally friendly alternative to traditional fossil fuels. Its production and use can help reduce pollution, enhance sustainability, and contribute to a greener future.

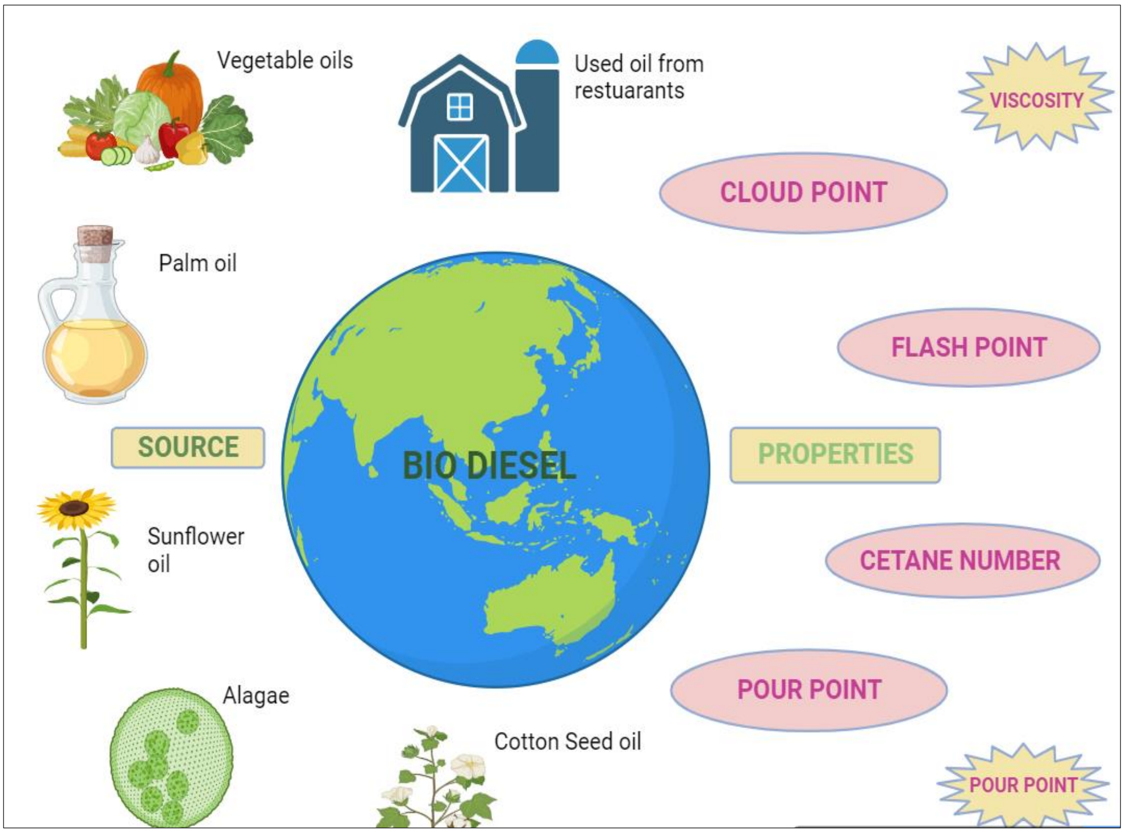

Fig. 2. Sources of Biodiesel and its properties with viscosity and pour point

3. PHYSICO-CHEMICAL PROPERTIES OF BIODIESEL

Fig. 3 illustrates the Physico-chemical properties of biodiesel, highlighting the key parameters that define its quality and performance in engines. These properties include density, viscosity, cetane number, flash point, pour point, cloud point, and acid value, among others. Density is an essential measure that affects the fuel's energy content and combustion characteristics; it typically ranges from 860 to 900 kg/m³ for biodiesel, which is slightly higher than conventional diesel [22]. Viscosity, a critical factor influencing fuel atomization and engine wear, generally falls between 1.9 and 6.0 mm²/s for biodiesel, ensuring proper lubrication while maintaining optimal flow through the engine's fuel system. Cetane number, a measure of a fuel's ignition quality, plays a significant role in engine performance and emissions. Biodiesel typically has a cetane number ranging from 47 to 67, indicating better ignition properties compared to traditional diesel. A higher cetane number leads to smoother combustion and reduced emissions of pollutants like NOx and particulate matter [23-24].

The flash point, indicating the temperature at which biodiesel vapors can ignite, is another crucial property. Biodiesel has a flash point typically above 130°C, providing a high level of safety in handling and storage [25]. Pour point and cloud point reflect the temperature thresholds at which biodiesel starts to gel or form waxy crystals, influencing its usability in colder climates. Biodiesel's pour point ranges from -10 to 15°C, and the cloud point from -3 to 12°C, depending on the feedstock used in its production [20]. Lastly, the acid value indicates the free fatty acid content, which impacts the fuel's stability and corrosion potential. A lower acid value, typically below 0.5 mg KOH/g, suggests a more stable biodiesel with reduced risk of engine corrosion. Overall, the physico-chemical properties depicted in Fig. 3 provide a comprehensive overview of the quality and performance benchmarks for biodiesel. Understanding these properties is essential for ensuring that biodiesel meets industry standards and can be effectively used as a sustainable alternative to traditional diesel fuels [26].

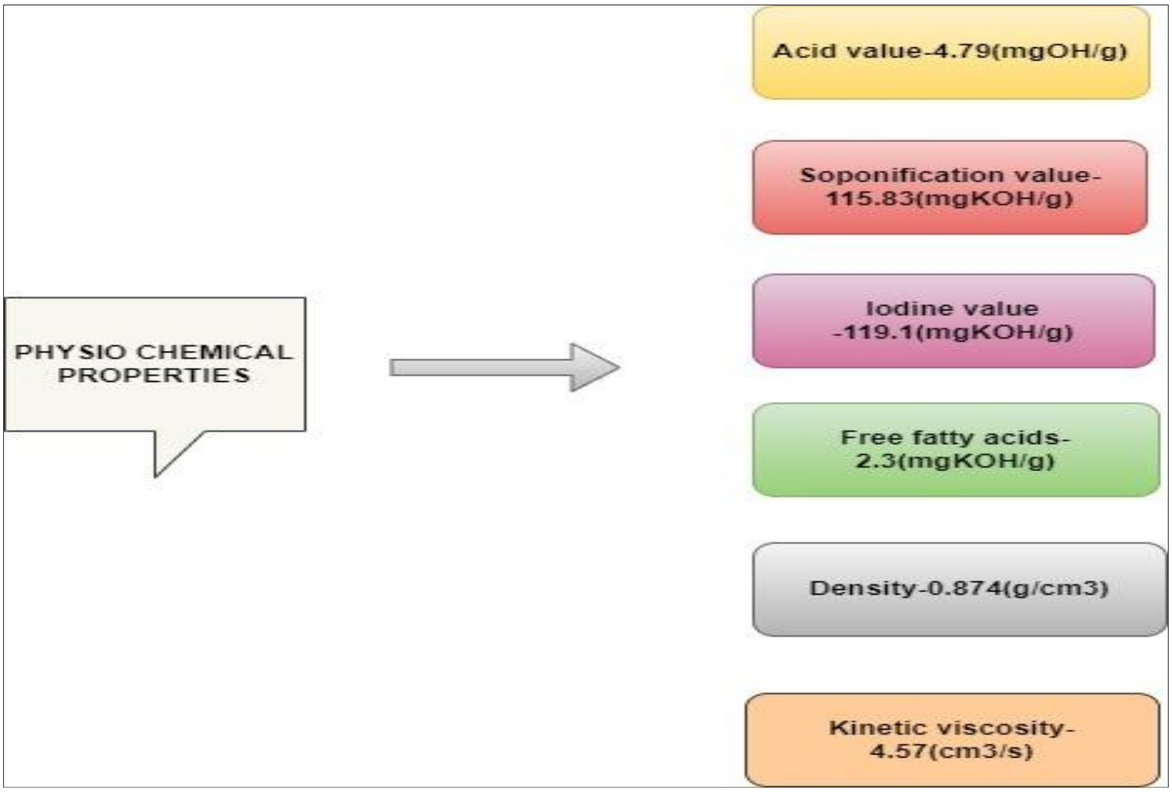

Fig. 3 Physio chemical properties of biodiesel

4. METHODS OF EXTRACTION OF BIODIESEL

Biodiesel, a renewable alternative to conventional diesel fuel, can be extracted from various feedstock such as vegetable oils, animal fats, and even algae. Two primary methods for biodiesel extraction are mechanical and chemical processes (Fig. 4), each with its own set of advantages and considerations.

4.1 Mechanical Method

In the mechanical method, also known as the "transesterification" process, biodiesel is extracted through a series of physical processes without the use of chemical catalysts. Here's a general overview of the steps involved:

a. Preparation of Feedstock: The feedstock, such as vegetable oil or animal fat, is first purified to remove any impurities or solid particles.

b. Transesterification: The purified feedstock is then mixed with an alcohol, usually methanol or ethanol, in the presence of a catalyst. Common catalysts include sodium hydroxide (NaOH) or potassium hydroxide (KOH).

c. Reaction: The mixture is agitated or stirred vigorously to facilitate the reaction between the alcohol and the triglycerides present in the feedstock. This reaction results in the formation of biodiesel (methyl or ethyl esters) and glycerol.

d. Separation: After the reaction is complete, the mixture is allowed to settle, allowing the glycerol, which is heavier, to separate from the lighter biodiesel.

e. Washing and Drying: The biodiesel is then washed with water to remove any remaining impurities or catalyst residues. Finally, it is dried to remove excess moisture.

Advantages of the mechanical method include its simplicity, lower operating costs, and reduced environmental impact compared to chemical methods. However, it may not be as efficient as chemical methods in converting all triglycerides into biodiesel, and it requires careful management of waste glycerol.

4.2. Chemical Method

The chemical method of biodiesel extraction involves the use of chemical catalysts to accelerate the transesterification reaction. Here's how it typically works:

a. Preparation of Feedstock: Similar to the mechanical method, the feedstock is prepared by removing impurities and solid particles.

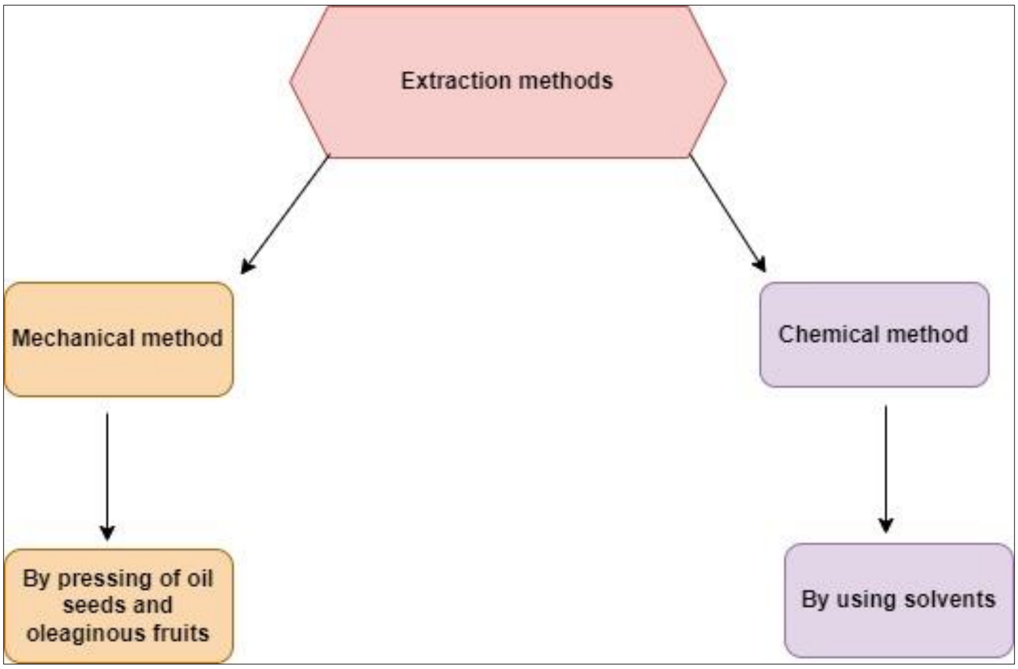

Fig. 4. Mechanical and Chemical method of Biodiesel extraction

b. Transesterification: The purified feedstock is mixed with alcohol (methanol or ethanol) and a chemical catalyst (usually NaOH or KOH) in a reactor vessel. The catalyst helps speed up the reaction between the alcohol and triglycerides.

c. Reaction: The mixture is heated and agitated to promote the transesterification reaction. This reaction converts triglycerides into biodiesel and glycerol.

d. Separation: After the reaction is complete, the mixture is allowed to settle, and the glycerol is separated from the biodiesel.

e. Neutralization and Washing: The biodiesel is then neutralized to remove any remaining catalyst and washed to remove impurities.

The chemical method typically yields higher biodiesel purity and conversion rates compared to the mechanical method. However, it requires more careful handling of chemicals, higher initial investment in equipment, and generates more waste products that need proper disposal [27]. Both methods have their place in biodiesel production, and the choice between them depends on factors such as feedstock type, scale of production, cost considerations, and environmental regulations. Additionally, ongoing research and development aim to improve both methods to make biodiesel production more efficient, cost-effective, and environmentally friendly [28].

5. DIFFERENT TYPES OF CATALYST USED IN EXTRACTION OF BIODIESEL

5.1 Homogenous Catalyst

Both acidic and alkaline catalysts play crucial roles in biodiesel production, with their solubility during the reaction being a defining characteristic. Acidic catalysts, such as H2SO4, are commonly employed in the esterification process, while alkaline catalysts like NaOH and KOH are utilized in transesterification [29]. Homogeneous catalysts offer several advantages, including easy availability and affordability, high conversion rates in shorter time frames, and the ability to catalyze reactions at lower temperatures and pressures [30,341. Alkaline catalysts are particularly effective for refined oils with minimal fatty acid content, typically less than 0.5% or an acid value below 1mgKOH per gram. However, the drawback of using alkaline catalysts lies in the need for extensive washing of the produced biodiesel with water to remove residual fatty acids, leading to the generation of large volumes of wastewater [32]. This washing process not only increases the overall cost of biodiesel production but also introduces the risk of corrosive reactions due to the use of water for catalyst removal. To prevent soap formation, it is essential to ensure that both alcohols and triglycerides are anhydrous, and the raw material's free fatty acid content is kept low.

Table 1. Comparison of three catalyst *viz.* Homogenous, Heterogeneous and Enzymatic [37-38]

Homogenous	Heterogenous	Enzymatic
Sophisticated equipment and techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FTIR) were needed.	Heterogeneous catalysts are created using a variety of techniques, including base metal impregnation, precipitation, calcination, and co-precipitation.	Compared to homogeneous and heterogeneous catalyst, the yield of biodiesel produced by enzymatic catalyst is relatively lower.
Statistical tools like Response surface methodology (RSM) using Central Composite Design(CCD) (experimental design) are essential to study the effects of process of variables in the reaction yield	In order to produce biodiesel, Borges and Diaz employed a packed bed catalytic reactor in a recirculating system to use potassium-loaded pumice material as the heterogeneous catalyst in the transesterification process between waste oil and sunflower oil	It is less expensive and requires less time for the reaction to occur.

5.2 Heterogeneous Catalyst

Solid catalysts, primarily metal oxides, play a vital role in biodiesel production, particularly for feedstocks containing solids and insoluble components. Heterogeneous catalysts like SrFe2O4, KBr, CaO [33], chitosan, and some derived from meat are favoured over homogeneous catalysts for several reasons. Firstly, they offer the advantage of reusability, allowing for multiple reaction cycles. Secondly, they facilitate better separation of products and result in higher quality oil [34]. Solid base catalysts are particularly preferred among heterogeneous catalysts due to their ease of removal, eliminating the need for washing, and allowing for straightforward regeneration [12,35]. Additionally, the use of solid base catalysts reduces the corrosive nature of the reaction, as less water is required for catalyst separation. Examples of solid base catalysts include mixed oxides, zeolites, sulphates, zircon, and ion exchange resins, which are primarily utilized for biodiesel production from feedstock with low free fatty acid content [36].

5.3 Enzymatic Catalyst

These are one of the most used catalyst for biodiesel production and both esterification and transesterification will be done during reaction.

6. FACTORS EFFECTING BIODIESEL PRODUCTION

Vegetable oil changes viscosity throughout the transesterification process. Low viscosity fuels will be produced by removing glycerol and other high viscosity components. The biodiesel's flash point will drop and its cetane number will rise following the transesterification process. Many variables affect the quality of biodiesel, including temperature, catalyst utilized, reaction time, moisture content, free fatty acid content, and the molar ratio of alcohol to oil.

6.1 Temperature

Good quality of biodiesel mainly depends on temperature. Higher the temperature the reaction rate also get increased by which the reaction time get decreased and the viscosity of the oil also decreases [39]. When the temperature increased above the optimal level than the quality of biodiesel get decreased which eventually make Saponification of triglycerides and also leads to vaporization of ethanol. The reaction temperature depends on nature of oils and fats used and optimal temperature relays between 50-60oC.To stop alcohols from evaporating, the transesterification reaction temperature needs to be lower than the boiling point of alcohol [40].

6.2 Reaction Time

A quicker reaction time results in a quicker conversion of fatty acid esters [41]. Because alcohol and oil disperse easily, the reaction will start out slowly but pick up speed later on and finish in around 90 minutes. Increased reaction time won't result in a faster conversion; instead, the reversible nature of transesterification—which results in the loss of esters and the creation of soap—will eventually cause the yield of biodiesel to drop [42].

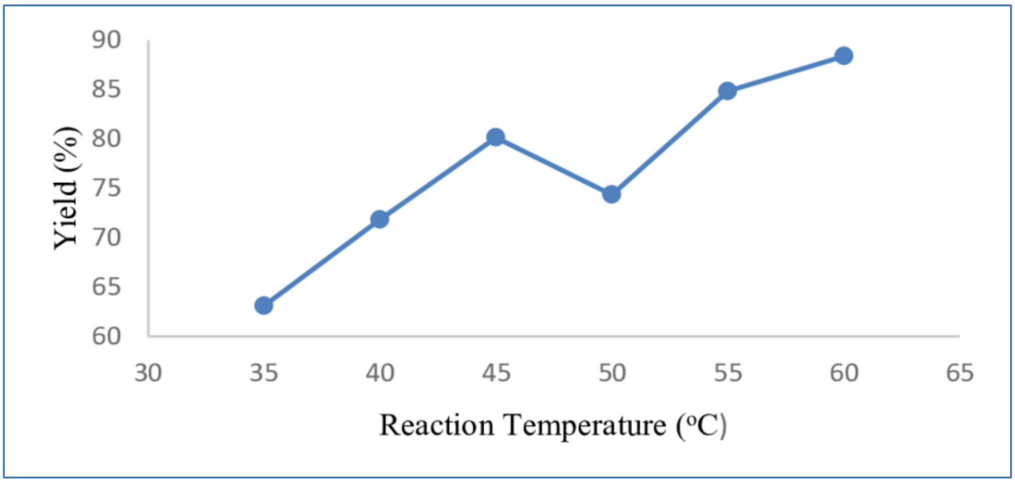

Fig. 5. Variation of yield due to temperature fluctuations

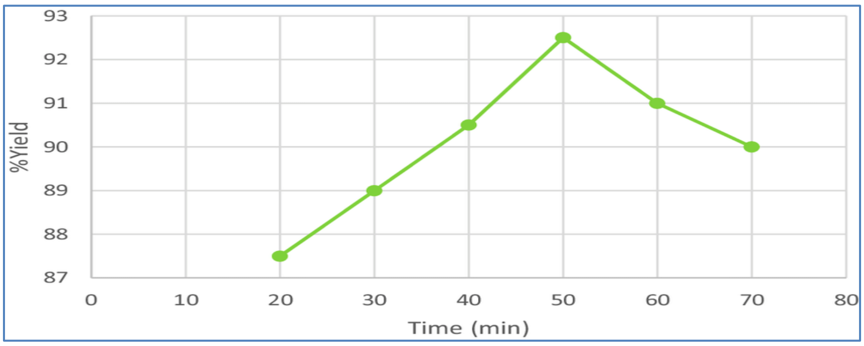

Fig. 6. Variation of yield due to reaction time

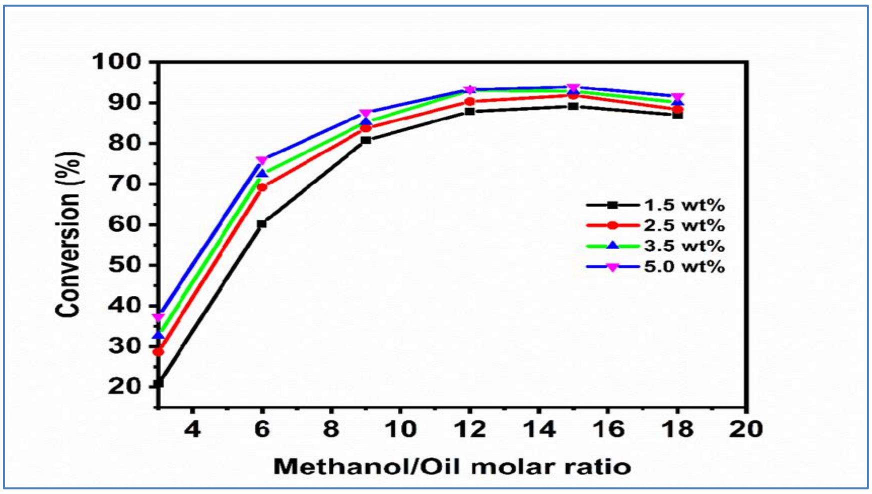

Fig. 7. Variation of conversion due to methanol to oil molar ratio

6.3 Methanol to Oil Molar Ratio

Since esterification is a reversible reaction, more alcohol can be added to the mixture or extra product can be eliminated to boost the biodiesel output. The reaction rate will be maximum when all of the methanol is utilized. Because it is inexpensive, polar, and a short chain alcohol, methanol is generally chosen over other alcohols such as ethanol, propanol, and so on. However, ethanol is preferred in the transesterification reaction because it can be generated from agricultural products, is renewable, and poses less of a biological threat to the environment. 99.5% biodiesel output at an oil to methanol ratio of 1:6 is the maximum that can be achieved [43,44]. The output of biodiesel has increased as methanol consumption has increased.

6.4 Types and Amount of Catalyst Used

The kind and quantity of catalyst we utilize will vary depending on the type, alcohol content, and technique employed. The most widely utilized catalysts in the manufacture of biodiesel are potassium hydroxide (KOH) and sodium hydroxide (NaOH) [45-46]. In the transesterification process, adding additional catalyst typically results in a higher ester yield; however, this is not profitable because catalyst is expensive. Therefore, producing biodiesel will require the best possible utilization of catalyst [47].

6.5 Mixing Intensity

Effective mixing plays a crucial role in the transesterification process and the production of esters, primarily because alcohol and oil do not readily mix and reactions occur at the interface between the two liquids [48]. Consequently, achieving optimal mixing between alcohols and oils is imperative, with the required level of mixing varying depending on the specific requirements of the transesterification process. Vegetable oils, characterized by their high viscosity, necessitate vigorous mechanical

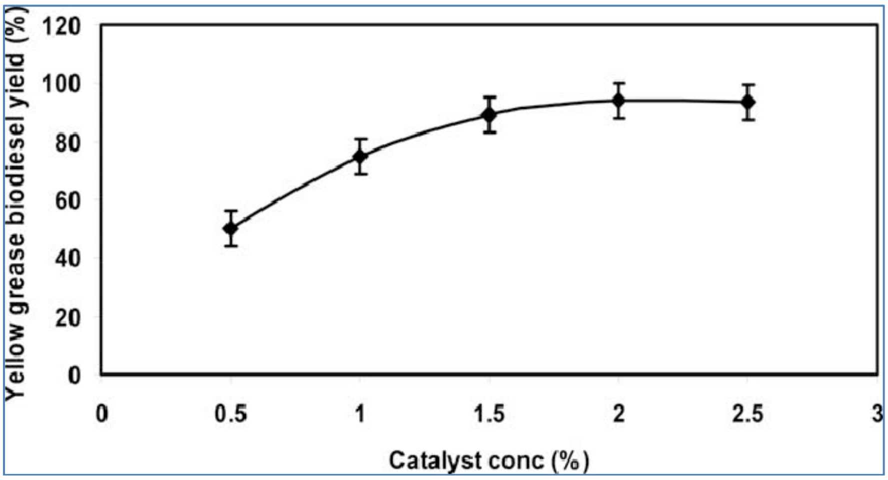

Fig. 8. Biodiesel yield

mixing to ensure thorough blending, although adjustments in the intensity of feedstock mixing can achieve consistent and satisfactory results. Research suggests that, during the transesterification reaction, the reactants initially form a two-phase liquid system [20,49]. It has been observed that mixing significantly influences the reaction's rate at this stage; however, as phase separation concludes, the impact of mixing diminishes.

6.6 Free Fatty Acid and Water Content

When employing a catalyst for the transesterification of glycerides with alcohol, the presence of free fatty acids and water content significantly influences the process. A free fatty acid content exceeding 1%w/w leads to the production of soap, complicating product separation (glycerol) and reducing biodiesel yield. Given the higher water content in waste cooking oil, the hydrolysis reaction intensifies while the formation of esters diminishes simultaneously [21-31]. Hence, the supercritical methanol approach is adopted to address this issue, as water exerts a minimal impact in this method. Maintaining a maximum water content of 0.5% is crucial to achieving a 90% biodiesel production rate [50]. Exceeding the 0.5% threshold renders acid-based catalyst reactions more perilous compared to base catalyst reactions, as alcohol reacts with free fatty acids, generating esters and water in the process [18].

7. FUTURE PERSPECTIVES

Utilizing waste cooking oil for sustainable biodiesel production holds promising future prospects, offering a dual solution to environmental and economic challenges. As technological advancements continue to refine conversion processes, the efficiency and cost-effectiveness of biodiesel production from waste cooking oil are set to improve, paving the way for scalable solutions. The integration of biodiesel production with circular economy initiatives will further bolster sustainability efforts, creating a symbiotic relationship between waste management and renewable energy production. Moreover, as governments worldwide increasingly prioritize environmental sustainability, the implementation of biofuel blending mandates could provide a significant boost to the demand for biodiesel, incentivizing the utilization of waste cooking oil as a valuable feedstock.

In tandem with technological advancements, regulatory frameworks and quality standards will play a crucial role in ensuring the integrity and sustainability of the biodiesel produced from waste cooking oil. Rigorous certification processes will provide assurance to consumers and stakeholders alike, fostering confidence in the environmental benefits and compatibility of biodiesel. Furthermore, collaborative efforts between governments, industry players, and research institutions will be essential in driving innovation, facilitating infrastructure development, and promoting widespread market adoption. By leveraging these combined efforts and increasing consumer awareness, the future of utilizing waste cooking oil for biodiesel production appears promising, poised to make significant strides towards a more sustainable and greener future.

8. CONCLUSION

Biodiesel emerges as a promising alternative fuel, offering environmental benefits as a renewable and biodegradable option for transportation. With diverse feedstock options ranging from animal fats to leftover cooking oil and algae, biodiesel production presents versatile solutions. Transesterification, a widely utilized process, relies on effective catalysts, particularly heterogeneous ones, to facilitate efficient conversion. Waste cooking oil serves as a cost-effective feedstock, with acid catalyst treatment reducing its high fatty acid content. Despite challenges such as water formation during esterification, step-by-step reaction mechanisms mitigate such issues. Methanol stands out as a preferred alcohol choice due to its affordability and ease of separation. Moving forward, selecting optimal process technologies and environmentally friendly catalysts will be crucial for enhancing the economic viability and sustainability of biodiesel production. This underscores the ongoing need for innovation and strategic decision-making in the biodiesel industry.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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