

Review of Revolutionizing Biofuel Production: Sustainable Methods for Converting Waste Cooking Oil into Biodiesel

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Abstract

The growing demand for sustainable energy has intensified research into biodiesel production from waste cooking oil (WCO), an eco-friendly and cost-effective feedstock. This review synthesizes advancements in WCO-to-biodiesel conversion technologies, focusing on transesterification methods including conventional, microwave-assisted, and enzymatic processes optimized through catalytic innovation (e.g., nanocatalysts) and process intensification (e.g., microwave irradiation). Key findings highlight microwave-assisted transesterification, achieving 97% yield with steel slag catalysts, while enzymatic methods offer high purity with minimal byproducts. Challenges like feedstock variability and scalability are addressed via techno-economic analyses and machine learning. The study underscores WCO biodiesel's environmental benefits, including reduced emissions and a 78% lower carbon footprint than fossil diesel, while emphasizing Malaysia's leadership in palm-based biodiesel under its National Biofuel Policy. Future directions include circular economy integration and advanced catalysis for industrial adoption.

Key Words: Biodiesel, Waste Cooking Oil, Transesterification, Catalysts, Sustainability

1.0 Introduction

The accelerating depletion of fossil fuel resources, coupled with escalating environmental concerns, has intensified global efforts to explore sustainable energy alternatives. Among these, biodiesel has emerged as a prominent renewable and biodegradable substitute for conventional diesel, offering considerable environmental benefits (Kumar et al., 2021). In particular, waste cooking oil (WCO), which is often discarded improperly, has been recognized as both a cost-effective and environmentally sustainable feedstock for biodiesel production. This approach not only addresses waste disposal challenges but also aligns with the principles of the circular economy, providing dual environmental benefits (Zhang et al., 2020).

As one of the world's leading producers of palm oil, Malaysia has strategically leveraged this abundant agricultural resource to develop a strong biodiesel industry. To capitalize on this advantage, the Malaysian government introduced the National Biofuel Policy (NBP) in 2006, aimed at promoting the commercialization of biodiesel, enhancing research and development, advancing technological capabilities, and creating export opportunities for palm-based biofuels (ARC Group, 2024). This comprehensive policy framework pursues three main objectives: reducing dependence on fossil fuels, strengthening national energy security, and stabilizing palm oil market prices to support the agricultural sector.

A key element of this policy is the progressive implementation of biodiesel blending mandates, designed to gradually increase the proportion of renewable content in conventional diesel fuel. The B10 program, introduced for the transportation sector, mandates a blend of 10% palm biodiesel with 90% petroleum diesel. Following this, the B20 program, primarily targeted at the industrial and transportation sectors, aims to incorporate 20% palm biodiesel in the blend. The B30 program represents an even more ambitious target of a 30% palm biodiesel mixture, further reducing reliance on fossil fuels (Malaysian Palm Oil Board (MPOB), 2023; Reuters, 2025). These blending initiatives are intended to lower greenhouse gas emissions, enhance energy security, and stimulate domestic demand for palm oil.

Recent industry data indicates that, as of 2024, Malaysia's biodiesel production capacity stands at approximately 2.76 million tonnes per year, with operational output from 19 active production facilities reaching around 906,153 tonnes annually (Nurul Eza *et. al.*, 2022). Although plans were established to escalate blending ratios to B20 and B30 nationwide, these ambitions have faced significant challenges, including infrastructural constraints and fluctuations in global crude palm oil prices (Reuters, 2025). Consequently, Malaysia has maintained the B10 standard as the nationwide mandate for the transportation sector, with annual biodiesel production expected to stabilize at approximately 1.58 billion liters (United States Department of Agriculture (USDA) Foreign Agricultural Service, 2024), reflecting a pragmatic response to technical and economic realities.

Despite these challenges, Malaysia continues to pursue the advancement of its biodiesel industry through a variety of strategic initiatives. Regulatory authorities have enhanced monitoring and enforcement mechanisms to curb fraudulent activities in the WCO supply chain, especially in light of growing international scrutiny regarding the origin of used cooking oil (UCO) exports (Reuters, 2025). Simultaneously, Malaysia is expanding its biofuel portfolio, with projections suggesting that its sustainable aviation fuel (SAF) production capacity will exceed regional demand by 2025. This anticipated surplus is expected to bolster export volumes while contributing to a reduction in global SAF prices (Reuters, 2025). Together, these developments highlight Malaysia's ongoing commitment to the growth of its biofuel sector and its adaptive approach to the evolving global energy landscape.

Building on its position as a global leader in palm oil production, Malaysia has firmly positioned itself at the forefront of biodiesel development. This leadership has been largely driven by the National Biofuel Policy introduced in 2006, which provides a robust framework for promoting sustainable biodiesel production and enforcing key blending mandates such as the B10, B20, and B30 programs (Lam *et al.*, 2010; MPOB, 2023). Notably, the development of Malaysia's biodiesel sector is guided by two overarching strategic objectives: enhancing national energy security and reducing dependence on conventional fossil fuels, thereby addressing both economic needs and environmental sustainability goals

2.0 Waste Cooking Oil as a Feedstock

Waste cooking oil (WCO), a byproduct generated from widespread vegetable oil usage in both commercial food operations and domestic settings, presents significant opportunities for sustainable resource utilization. Importantly, WCO serves not merely as an economical feedstock but also as a solution to pressing waste management challenges, thereby substantially reducing environmental contamination (Hamze *et al.*, 2024). The scale of this resource is considerable, with the European Union alone producing between 0.7 to 1 million tons of WCO each year (LMC International, 2021). Particularly in palm oil-producing nations like Malaysia, where WCO generation is substantial, this waste stream has gained recognition as a valuable biodiesel feedstock. This application offers a dual advantage: it provides a cost-competitive alternative to expensive virgin vegetable oils while simultaneously addressing the ecological impacts of improper WCO disposal.

Waste cooking oil (WCO) is recognized as an efficient and sustainable feedstock for biodiesel production. One of its key advantages lies in its cost-effectiveness, as it is considerably less expensive than virgin vegetable oils, thus offering a financially viable option for large-scale biodiesel manufacturing (Said *et al.*, 2015). Moreover, the utilization of WCO contributes significantly to environmental conservation by addressing waste

disposal challenges and decreasing dependence on fossil fuels, thereby fostering greater sustainability (Badli, 2021). Among the various methods available, transesterification remains the most widely employed technique for converting WCO into biodiesel. This process involves the chemical reaction of WCO with an alcohol typically methanol in the presence of a catalyst, which leads to the formation of fatty acid methyl esters (biodiesel) and glycerol as a byproduct (Akmar et al., 2018). The overall efficiency of this conversion is influenced by several operational parameters, including reaction time, temperature, and the type of catalyst used.

Despite its numerous advantages, the utilization of waste cooking oil (WCO) for biodiesel production is not without challenges. Notably, the quality of WCO can vary considerably depending on its source and previous usage conditions, which in turn may impact both the efficiency of the conversion process and the quality of the resulting biodiesel (Yusof et al., 2024).

In addition, the collection and transportation of WCO necessitate a well-developed infrastructure to maintain a consistent and reliable feedstock supply for biodiesel production (Ogundipe & Babarinde, 2017). To address these limitations, the implementation of more efficient collection systems and the enhancement of refining techniques are essential for improving the overall feasibility of WCO-based biodiesel as a sustainable energy alternative. In response to these issues, recent studies have increasingly focused on optimizing production methods to maximize biodiesel yields from low-cost feedstocks such as WCO.

In particular, research efforts have examined the potential of WCO for biodiesel production in several Asian countries, including Malaysia, which stands out as a leading producer and consumer of palm oil (Yusof et al., 2024). Figure 1 displays two samples in transparent containers: waste cooking oil (WCO) on the left and the biodiesel produced from it on the right. The visual comparison highlights a key indicator of successful transesterification the improvement in clarity and color of the final biodiesel product.



Figure 1: Waste cooking oil and biodiesel produced

3.0 Biodiesel Production Methods from WCO

In Malaysia, biodiesel production primarily relies on palm oil as the main feedstock, capitalizing on the nation's abundant palm oil resources (Lam et al., 2020). The predominant technique used is transesterification, whereby triglycerides present in palm oil undergo a chemical reaction with methanol in the presence of a catalyst, resulting in the formation of fatty acid methyl esters (FAME) commonly referred to as biodiesel and glycerol as a

byproduct (Shamsuddin & Abdullah, 2022). This method is widely adopted owing to its high efficiency and the substantial yield of biodiesel it produces.

Table 1 compares different catalyst types used in the transesterification process for biodiesel production. Alkaline catalysts such as NaOH and KOH offer fast reaction rates and high yields at low cost but are unsuitable for high free fatty acid (FFA) feedstocks due to soap formation. Acid catalysts like H₂SO₄ work well with high-FFA feedstocks but are corrosive and require longer reaction times. Enzymatic catalysts, particularly lipase, are eco-friendly and reusable, though they are costly and exhibit slower reaction rates.

Table 1: Comparison of Catalyst Types in Transesterification Process

Catalyst Type	Reaction Rate	Advantages	Disadvantages
Alkaline (NaOH, KOH)	Fast	High yield, low cost	Sensitive to free fatty acids, soap formation
Acid (H ₂ SO ₄)	Slow	Effective for high-FFA feedstocks	Corrosive, requires longer reaction time
Enzymatic (Lipase)	Moderate	Eco-friendly, reusable	Expensive, slow reaction rate

Recent advancements in biodiesel production methods in Malaysia have increasingly emphasized the enhancement of both efficiency and sustainability. Among these innovations, the adoption of non-catalytic supercritical methanol processes represents a significant breakthrough, as it eliminates the need for catalysts and streamlines the purification stage (Ayoola et al., 2024). In parallel, microwave-assisted transesterification has been explored for its potential to accelerate reaction rates while improving energy efficiency (Shamsuddin & Abdullah, 2022). Collectively, these emerging technologies are designed to overcome persistent challenges such as feedstock price volatility and the environmental impacts associated with conventional biodiesel production methods (Lam et al., 2020).

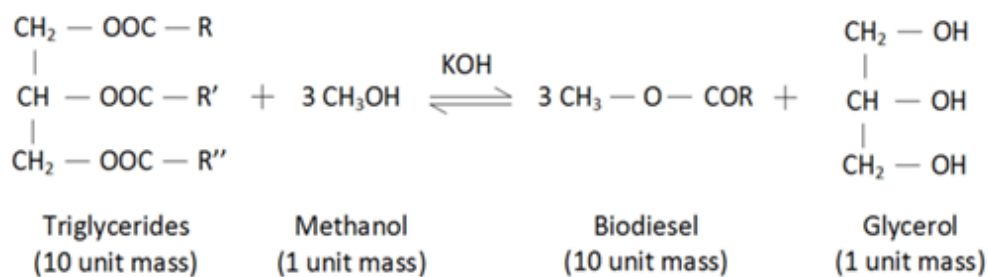


Figure 2: Transesterification Chemical Reaction (Chong, William & Ng, J.-H., 2016).

Despite these technological advancements, the Malaysian biodiesel industry continues to encounter several challenges, notably the competition between biodiesel production and food-related applications for palm oil, as well as the ongoing need for technological enhancements to improve process sustainability and minimize environmental impacts (Ayoola et al., 2024). In response, current research is increasingly focused on the utilization of alternative feedstocks such as waste cooking oil (WCO) and microalgae to diversify biodiesel sources and address these limitations (Shamsuddin & Abdullah, 2022). To support this shift, various conversion methods have been developed for transforming WCO into biodiesel, including conventional transesterification, microwave-assisted transesterification, and enzymatic transesterification.

3.1. Transesterification Process

Transesterification remains the primary method for biodiesel production, involving a chemical reaction between triglycerides (derived from fats or oils) and an alcohol typically methanol in the presence of a catalyst, resulting in the formation of fatty acid methyl esters (biodiesel) and glycerol as a byproduct (Kumar et al., 2021; Saleh & Putri, 2024). Catalysts used in this process are generally classified into two main types: homogeneous catalysts, such as sodium hydroxide, and heterogeneous catalysts, such as calcium oxide, each offering distinct advantages in terms of reaction efficiency and ease of product separation.

Table 2 presents the classification of homogeneous and heterogeneous catalyst types used in the transesterification process, along with their respective advantages and disadvantages. In addition to catalyst selection, the efficiency and yield of transesterification are also influenced by four key process parameters, as summarized in Table 3. These factors include alcohol-to-oil molar ratio, catalyst concentration, reaction temperature and time, and feedstock quality all of which significantly impact the overall biodiesel production performance.

Table 2: Classification of Catalyst Types in Transesterification

Catalyst Type	Example	Advantages	Disadvantages	References
Homogeneous Catalysts				
Alkaline Catalysts	NaOH, KOH	High activity, cost-effective	Sensitive to free fatty acids and water, may cause soap formation	Kim et al., 2024; Tan et al., 2023; Lee & Wong, 2022; Jain & Sharma, 2022; Basu & Sharma, 2022
Acid Catalysts	H ₂ SO ₄	Effective for high free fatty acid feedstocks	Highly corrosive, longer reaction times, higher energy consumption, difficult separation	Kim et al., 2024; Ahmad et al., 2021; Patel et al., 2023; Goh & Lee, 2023; Singh & Patel, 2022
Heterogeneous Catalysts				
Base Catalysts	CaO	Reusable, cost-effective	Lower activity compared to homogeneous catalysts	Saleh & Putri, 2024; Zhang et al., 2023; Lim et al., 2022; Nguyen & Pham, 2024; Xu & Zhao, 2023
Acid Catalysts	Solid superacids	Can catalyze esterification and transesterification	Highly corrosive, complex separation, high operational cost	Saleh & Putri, 2024; Wang et al., 2023; Hassan & Noor, 2021; Alaba & Olutoye, 2021; Liew & Chew, 2023
Enzyme-Based Catalysts	Lipases	High-purity biodiesel, no byproduct formation	High cost, longer reaction times	Kim et al., 2024; Rahman et al., 2022; Chia & Ng, 2023; Sulaiman & Ismail, 2023; Kumar & Singh, 2024

Table 3: Factors and impacts of process parameters influencing transesterification

Factor	Impact	References
1. Alcohol-to-Oil Molar Ratio	Excess alcohol drives reaction completion but complicates glycerol separation	Saleh & Putri, 2024; Kumar et al., 2023; Yusof et al., 2022
2. Catalyst Concentration	Optimal loading ensures maximum conversion; excess catalyst may cause soap formation	Saleh & Putri, 2024; Hassan et al., 2023; Zhang & Lim, 2021
3. Reaction Temperature & Time	Elevated temperatures improve reaction rates but may trigger unwanted side reactions	Saleh & Putri, 2024; Nguyen et al., 2023; Chen & Zhao, 2022
4. Feedstock Quality	Impurities, water, and free fatty acids can lower yields and cause soap formation	Kim et al., 2024; Singh & Patel, 2023; Rahman et al., 2022

**Figure 3 :** WCO Biodiesel transesterification processing reactor (Azmi *et al.*, 2023)

Recent research efforts advancements in transesterification have increasingly focused on the development of more efficient and sustainable catalysts to enhance biodiesel production. Among these innovations, nanocatalysts have garnered significant attention due to their high surface area and unique physicochemical properties, which contribute to improved catalytic activity and selectivity (Kim et al., 2024). Additionally, bifunctional catalysts capable of simultaneously facilitating both esterification and transesterification reactions have proven particularly advantageous when processing low-quality feedstocks with high free fatty acid content (Kim et al., 2024).

3.2. Microwave-Assisted Transesterification

Microwave-assisted transesterification represents a promising advancement in biodiesel production, utilizing microwave irradiation instead of conventional heating methods to enhance process performance. This technique offers several advantages, including significantly reduced reaction times, improved biodiesel yields, and greater overall process efficiency (Kim et al., 2024). In contrast to traditional heating, microwave energy ensures uniform heat distribution, thereby promoting more effective mass and heat transfer during the reaction (Saleh & Putri, 2024). During this process, waste cooking oil (WCO) or other lipid-based feedstocks are reacted with methanol or, in some cases, ethanol in the presence of a catalyst under microwave irradiation. The rapid and uniform

heating provided by microwaves accelerates the reaction rate considerably compared to conventional thermal methods (Ahmad et al., 2023).

Microwave irradiation provides uniform heating, accelerating the transesterification process. An innovative approach utilized unmodified steel slags as a catalyst under microwave irradiation, achieving a 97% conversion of WCO into biodiesel under optimized conditions (Derobertis et al., 2024). Figure 4 presents a flowchart of the microwave-assisted transesterification process for biodiesel production.

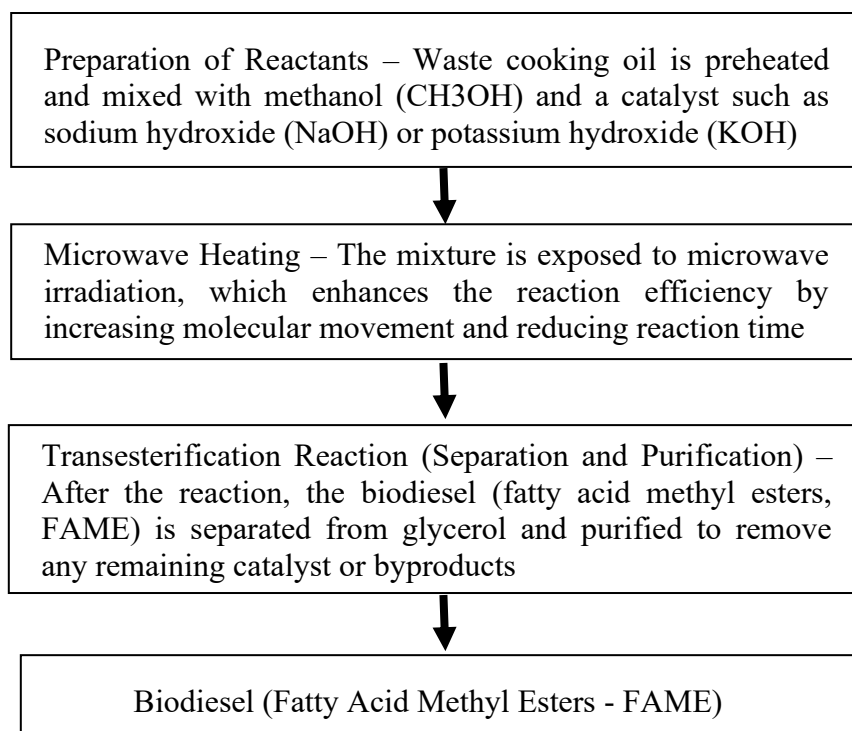


Figure 4: Microwave-assisted transesterification process (Rahman et al., 2022, Kim et al., 2024; Saleh & Putri, 2024)

Table 4: Advantages of Microwave-Assisted Transesterification

Advantage	Description	Reference
1. Reduced Reaction Time	Significantly shortens reaction duration from hours to minutes.	Kim et al. (2024)
2. Increased Biodiesel Yield	Enhances biodiesel yield through efficient and uniform heat distribution.	Saleh & Putri (2024)
3. Enhanced Energy Efficiency	Consumes less energy compared to conventional heating methods.	Ahmad et al. (2023)
4. Improved Catalyst Performance	Enhances the effectiveness of both homogeneous and heterogeneous catalysts.	Rahman et al. (2022)

Table 4 summarizes the key advantages of microwave-assisted transesterification in biodiesel production. This technique significantly reduces reaction time, enhances biodiesel yield, improves energy efficiency, and boosts catalyst performance, making it a more sustainable and effective alternative to conventional heating methods. Meanwhile Figure 5 illustrates the microwave-assisted transesterification process, where microwave irradiation

provides rapid and uniform heating of the reactant mixture. This accelerates molecular interaction, shortens reaction time, and increases overall biodiesel conversion efficiency .

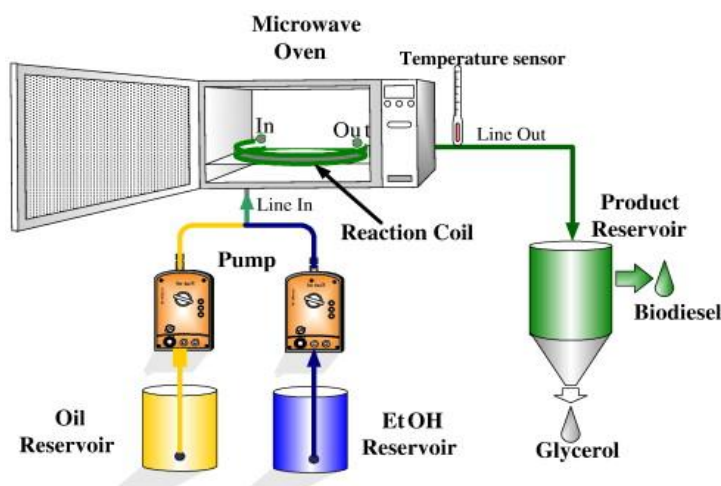


Figure 5: The microwave-assisted transesterification process (Dang Nguyen Thoai, 2020)

3.3. Enzymatic Transesterification

Enzymatic transesterification presents an alternative and environmentally friendly method for biodiesel production by employing lipase enzymes as catalysts, rather than conventional chemical catalysts such as sodium hydroxide (NaOH) or potassium hydroxide (KOH). This enzymatic approach offers several advantages, including lower energy requirements, milder reaction conditions, and reduced soap formation, thereby contributing to a more sustainable and cleaner production process (Zhou et al., 2023).

Lipase enzymes facilitate the transesterification reaction under these gentler conditions, yielding high-purity biodiesel with minimal by-product formation. Nevertheless, the widespread adoption of this method is constrained by the high cost of enzymes, which poses a significant challenge for large-scale implementation (Hanifa et al., 2022). In this process, triglycerides sourced from waste cooking oil or other lipid feedstocks react with an alcohol, typically methanol or ethanol, in the presence of lipase enzymes. These biocatalysts promote the conversion of triglycerides into fatty acid methyl esters (FAME), commonly known as biodiesel, along with glycerol as a byproduct (Chen et al., 2021).

Table 5: Key Steps, Advantages, and Challenges of Enzymatic Transesterification

Category	Description	Reference
Key Steps		
1. Selection of Lipase Enzyme	Lipases from <i>Candida antarctica</i> , <i>Rhizopus oryzae</i> , or <i>Pseudomonas cepacia</i> are commonly used.	Sharma et al., 2022
2. Reaction Conditions	Mild temperature (30–50°C) and lower alcohol-to-oil molar ratios reduce methanol usage.	Hernández-Martín & Otero, 2020
3. Biodiesel & Glycerol Separation	Separated by simple decantation or centrifugation after the reaction.	Gupta et al., 2024
Advantages		
1. Mild Reaction Conditions	No need for strong acids or bases; safer and more sustainable.	Chen et al., 2021
2. Higher Biodiesel Purity	Reduces soap formation and simplifies purification.	Sharma et al., 2022

Category	Description	Reference
3. Reusability of Lipases	Immobilized enzymes can be reused, reducing overall production costs.	Gupta et al., 2024
4. Tolerates High FFA Feedstocks	Can directly process oils with high free fatty acid (FFA) content without pretreatment.	Hernández-Martín & Otero, 2020
Challenges		
1. Higher Initial Cost	Lipase enzymes are more expensive than chemical catalysts.	Zhou et al., 2023
2. Longer Reaction Time	The enzymatic process is slower compared to chemical transesterification.	Gupta et al., 2024
3. Enzyme Inactivation	Methanol can inhibit lipase activity, requiring careful optimization of the reaction.	Sharma et al., 2022

4.0 Technological Advancements and Innovations

In recent years, considerable advancements have been directed toward enhancing both the efficiency and sustainability of biodiesel production processes. These developments have encompassed a range of technological innovations, including the refinement of transesterification methods, the introduction of novel catalytic systems, and the incorporation of energy-saving techniques. Moreover, researchers have increasingly prioritized process optimization strategies such as reducing reaction time, minimizing energy input, and utilizing renewable or low-cost feedstocks to ensure that biodiesel production not only yields higher outputs but also aligns with environmental and economic sustainability goals. Collectively, these efforts represent a paradigm shift towards cleaner, more efficient, and industrially viable biofuel technologies.

4.1. Computational Chemistry and Machine Learning

The integration of computational chemistry with machine learning has emerged as a powerful approach for optimizing biodiesel production, significantly improving yield and lowering production costs. By leveraging advanced data-driven modelling and simulation techniques, these technologies enable accurate prediction of optimal reaction parameters such as temperature, pressure, molar ratios, and reaction time—as well as the evaluation of catalyst efficiency and stability (Hamze et al., 2024). Furthermore, machine learning algorithms can analyse large experimental datasets to identify complex patterns and relationships that are not easily discernible through conventional methods, thereby accelerating the development of more efficient biodiesel production pathways. This synergy between computational tools and experimental data plays a crucial role in advancing sustainable and economically viable biodiesel technologies.

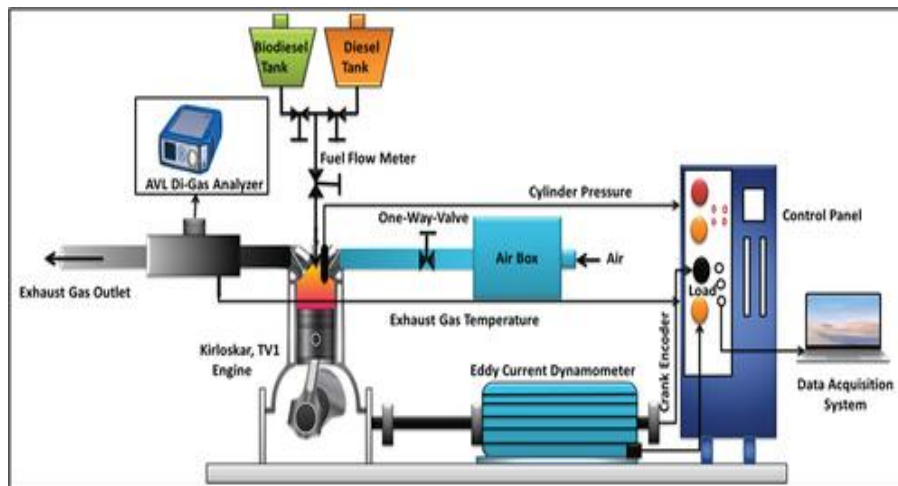


Figure 6: Enhancing waste cooking oil biodiesel yield and characteristics through machine learning, response surface methodology, and genetic algorithms for optimal utilization in CI engines (Ahmad et al., 2023).

4.2. Integrated Processes

Integrating biodiesel production with complementary processes such as bioethanol production, anaerobic digestion, or organic waste treatment has been shown to significantly enhance overall system efficiency and promote greater sustainability. Such integrated biorefinery approaches allow for the more efficient utilization of feedstocks, reduction of waste, and generation of multiple value-added products, thereby improving both environmental performance and economic viability. In support of these developments, techno-economic and environmental impact assessments have been conducted, demonstrating the potential advantages of these synergistic systems in terms of cost reduction, energy savings, and lower greenhouse gas emissions (Zhang et al., 2020). These findings underscore the promise of integrated processing strategies as a pathway toward more sustainable and circular biofuel production models.

5.0 Environmental and Economic Benefits

The utilization of waste cooking oil (WCO) as a feedstock for biodiesel production presents substantial environmental and economic advantages. Environmentally, this approach contributes to waste reduction by diverting used oils from landfills and waterways while simultaneously lowering greenhouse gas emissions associated with fossil fuel combustion. In addition to these benefits, Table 6 highlights the notable fuel quality advantages of biodiesel derived from WCO when compared to conventional diesel fuel. For instance, WCO biodiesel exhibits a higher cetane number (58 versus 50), which translates to improved combustion quality, better engine performance, and reduced ignition delay (Rahman et al., 2022). Furthermore, its significantly lower sulfur content (<10 ppm compared to 500 ppm) makes WCO biodiesel a cleaner-burning alternative, contributing to reduced sulfur oxide emissions and improved air quality. While WCO biodiesel has a slightly lower heating value than commercial diesel, its higher density and viscosity enhance fuel lubricity, potentially extending engine life and reducing maintenance requirements (Saleh & Putri, 2024). Collectively, these properties establish WCO biodiesel as a more environmentally friendly and engine-compatible alternative to conventional diesel fuel.

Table 6: Comparison of Properties Between Biodiesel from WCO and Commercial Diesel Fuel (Rahman et al., 2022; Saleh & Putri, 2024).

Property	WCO Biodiesel	Commercial Diesel
Density (kg/m ³)	880	850
Viscosity (mm ² /s)	4.5	2.5
Cetane Number	58	50
Sulfur Content (ppm)	<10	500
Heating Value (MJ/kg)	37	45

From an economic perspective, WCO serves as a low-cost and readily available substitute for virgin vegetable oils, thus lowering raw material costs and improving the overall feasibility of biodiesel production. Moreover, the transformation of a common household and industrial waste into a valuable energy resource aligns with circular economy principles and reinforces sustainable waste management practices (Financial Times, 2024). This approach not only reduces environmental burdens but also creates new value chains within the waste management and renewable energy sectors.

In the Malaysian context, the favorable properties of WCO-based biodiesel further enhance its economic appeal. Its acceptable fuel characteristics, including viscosity, cetane number, and calorific value, enable its use in existing diesel engines with minimal technical modifications (Rahman et al., 2022; Saleh & Putri, 2024). This minimizes the need for costly engine adaptations and facilitates quicker market adoption. Furthermore, the use of WCO as an alternative feedstock reduces the nation's reliance on palm oil for biodiesel production, thereby insulating Malaysia's economy from fluctuations in global vegetable oil prices (Zhang & Lim, 2021). The collection, processing, and distribution of WCO also create employment opportunities, particularly among small and medium enterprises involved in waste recovery and biofuel production (Singh & Patel, 2023).

Finally, the expansion of WCO-based biodiesel production contributes directly to Malaysia's national energy security goals by reducing dependence on imported fossil fuels and advancing the country's renewable energy targets (USDA Foreign Agricultural Service, 2024). Taken together, these environmental, economic, and policy-related factors position WCO-derived biodiesel as a strategic contributor to Malaysia's long-term energy sustainability and economic resilience.

6.0 Challenges and Future Prospects

Despite its promising potential, biodiesel production from waste cooking oil (WCO) continues to face persistent technical and logistical challenges. A key concern is the variability in both the availability and quality of collected WCO, which can significantly affect the consistency and efficiency of the transesterification process. Variations in compositional factors such as free fatty acid (FFA) content, moisture, and impurities may reduce catalyst activity, increase soap formation, and ultimately lower biodiesel yields (Reuters, 2024). Moreover, the heterogeneous nature of WCO often requires pretreatment steps, adding complexity and cost to production. Beyond feedstock issues, another major challenge lies in the limited adaptability and performance of current processing technologies. Many existing systems are designed for high-quality, uniform feedstocks and are not fully optimized for low-grade inputs like WCO. Additionally, reliance on costly catalysts and energy-intensive processes presents barriers to scalability, especially in resource-constrained regions where cost and energy access are critical. These challenges

underscore the need for innovation in feedstock standardization, catalyst development, and process optimization to fully realize the potential of WCO-based biodiesel production.

To overcome the current limitations associated with biodiesel production from waste cooking oil (WCO), future research should strategically focus on the development of cost-effective, reusable catalysts particularly those capable of withstanding high levels of free fatty acids (FFA) commonly present in low-quality feedstocks. Equally important is the systematic optimization of key production parameters, including reaction temperature, time, and the alcohol-to-oil molar ratio, all of which play critical roles in maximizing conversion efficiency and overall process performance. In parallel, the adoption of advanced processing technologies such as microwave-assisted and enzymatic transesterification offers significant potential to reduce energy consumption, shorten reaction durations, and minimize environmental impact.

Moreover, the successful scaling of WCO-based biodiesel production depends heavily on the establishment of a robust and standardized collection infrastructure. This includes not only the logistical framework for efficient WCO recovery from households and commercial sources but also public education campaigns to encourage participation, regulatory mechanisms to support compliance, and coordinated partnerships between governmental bodies, private industry, and the food service sector. Looking forward, the integration of digital innovations such as machine learning for predictive optimization, life cycle assessment (LCA) for environmental benchmarking, and circular economy principles for resource efficiency can further enhance the sustainability and resilience of biodiesel systems. Collectively, these interdisciplinary strategies will be instrumental in addressing existing technical and operational barriers, thereby unlocking the full potential of WCO as a renewable, economically viable, and environmentally sustainable energy resource.

7.0 Conclusion

The production of biodiesel from waste cooking oil (WCO) presents a sustainable and economically viable alternative to fossil fuels, offering significant environmental benefits. By converting WCO into biodiesel, both waste reduction and greenhouse gas emission mitigation can be achieved, while reducing dependence on virgin vegetable oils. Advances in conventional, microwave-assisted, and enzymatic transesterification methods have contributed to enhanced process efficiency, improved biodiesel yield, and superior fuel quality. Furthermore, catalytic innovations, including the use of heterogeneous and nanocatalysts, have been instrumental in improving reaction rates, product purity, and overall environmental performance.

Despite these technological advancements, several challenges continue to hinder large-scale WCO-based biodiesel production. The variability of WCO feedstock, the high cost of advanced catalysts, and the complexity of scaling production processes remain key obstacles. Nevertheless, the adoption of integrated solutions, such as process intensification, machine learning applications, and circular economy models, holds significant promise for overcoming these limitations. Emerging techniques, particularly microwave-assisted processes known for their energy efficiency and speed, alongside enzymatic approaches offering greener, low-waste alternatives, further support the feasibility of sustainable biodiesel production.

In the Malaysian context, strong government policy support and an established palm oil industry provide a solid foundation for continued biodiesel sector growth. However, to ensure long-term sustainability and alignment with the United Nations Sustainable Development Goals (SDGs), greater emphasis must be placed on transitioning toward non-edible and

waste-derived feedstocks such as waste cooking oil (WCO). This transition directly supports SDG 12 (Responsible Consumption and Production) by promoting the valorization of waste materials and reducing reliance on food-based resources for energy production. Future efforts should focus on improving WCO collection infrastructure, enhancing catalyst reusability, and investing in scalable, eco-friendly technologies, which align with SDG 9 (Industry, Innovation, and Infrastructure) and SDG 7 (Affordable and Clean Energy) by fostering sustainable industrial practices and expanding access to clean energy alternatives.

Moreover, by fostering cross-sector collaboration and aligning national initiatives with global sustainability targets, WCO-based biodiesel can play a pivotal role in the renewable energy transition, supporting both SDG 13 (Climate Action) and SDG 17 (Partnerships for the Goals). With continued innovation, policy alignment, and strategic investment, biodiesel derived from WCO can contribute meaningfully to cleaner energy systems, resource efficiency, and environmental preservation at both national and global levels. Such advancements are essential for Malaysia to achieve its SDG commitments while ensuring energy security, economic resilience, and environmental stewardship.

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