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REVIEW ARTICLE

A Review of Process Intensification Strategies in Biodiesel Production from Waste Cooking Oil to Enhance Efficiency and Sustainability

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Abstract

The global energy crisis and environmental concerns from fossil fuel use have driven the development of renewable biofuels. Biodiesel produced from waste cooking oil (WCO) is a promising option due to its low cost, wide availability, and non-competition with food resources. However, WCO typically contains high levels of free fatty acids (FFA), moisture, and impurities that hinder efficient conversion.This review highlights recent advances in process intensification strategies to improve WCO-based biodiesel production. Pretreatment methods such as heating, filtration, and centrifugation reduce contaminants, while acid esterification lowers FFA before transesterification. The physicochemical properties of WCO, particularly acid value and viscosity, are critical for setting optimal reaction conditions. Catalysts like NaOH (homogeneous), CaO from waste shells (heterogeneous), and bifunctional Mo_7-Zn_3/CaO are widely used to enhance reaction efficiency. Advanced reactors—especially microwave- and ultrasonic-assisted systems—significantly improve yield and energy efficiency. For instance, microwave-assisted transesterification using Mo_7-Zn_3/CaO achieves 94–96% biodiesel yield within 5–10 minutes at 65 °C, reducing energy consumption by up to 40% compared to conventional methods. Most approaches meet ASTM D6751 and EN 14214 fuel quality standards. Life cycle assessments show that WCO biodiesel can reduce greenhouse gas emissions by 75–80% compared to fossil diesel. The use of waste-derived catalysts and recycling of by-products such as glycerol supports circular economy goals. Nonetheless, challenges like variable WCO quality and high capital costs for advanced reactors remain. Future work should focus on scalable reactor development, real-time monitoring, and supportive policy frameworks to promote sustainable biodiesel production at an industrial level.

Keywords: Biodiesel, Waste Cooking Oil (WCO), Transesterification, Process Intensification, Heterogeneous Catalyst, Microwave-assisted Transesterification, Sustainable Biofuel**.**

1. Introduction

The global energy crisis and the environmental impacts of fossil fuel consumption have driven the development of more sustainable and eco-friendly renewable fuels [1]. A promising solution is biodiesel, particularly from waste feedstocks like waste cooking oil (WCO) [2]. WCO offers advantages such as low production costs, abundant availability, avoidance of food-fuel conflicts, and environmental benefits. However, the variable quality of WCO, especially its high free fatty acid (FFA) content—often exceeding 5%—remains a major challenge in biodiesel production [3]. High FFA levels react with alcohol to form soap, reducing biodiesel yield, causing technical issues, and increasing product acidity, which risks corrosion in storage tanks and engines [4]. Thus, pretreatment steps like acid esterification or degumming are required to reduce FFA content below recommended thresholds [5].Transesterification can be performed using chemical catalysts (acid or alkaline), enzymes like lipases, or under high-temperature/pressure conditions without catalysts [6]. Reaction efficiency depends on factors such as feedstock quality, FFA and moisture content, type and amount of alcohol and catalyst, mixing intensity, and process temperature/pressure [6]. To address these challenges, process intensification approaches are needed to enhance the efficiency and sustainability of WCO-based biodiesel production. Technologies like microwave-assisted and ultrasonic-assisted irradiation have proven effective in accelerating reactions, reducing energy consumption, and lowering production costs [7]. These methods optimize mass and heat transfer and reaction kinetics to significantly improve conversion efficiency [8]. Innovations such as reusable heterogeneous catalysts and bifunctional catalysts—capable of simultaneous esterification and transesterification—are also being developed [9]. The application of ultrasonic-assisted reactors [9], microwave-assisted systems [10], and membrane reactors [11], further enhances reaction rates and overall process efficiency.

Beyond technical aspects, economic and environmental factors are critical in WCO-based biodiesel production. Studies show that production costs can be reduced by optimizing reusable heterogeneous catalysts, such as ZnO- or TiO_2-modified CaO catalysts from snail shells, which achieve biodiesel yields of 90–95% [12]. Additionally, integrating glycerol byproduct recycling into circular bioeconomy platforms—through co-valorization with domestic waste, lignocellulosic biomass, or protein waste—improves sustainability and adds [13]. Environmentally, life cycle assessments (LCA) reveal that WCO biodiesel reduces greenhouse gas emissions by 60–80% compared to fossil diesel, though challenges like water eutrophication from energy use in production persist [14].Another issue is the global variability of WCO composition, where impurities like food particles, water, and heavy metals depend on collection sources and practices [15]. Standardizing WCO quality through government regulations and economic incentives is crucial for industrial-scale adoption [16]. Recent innovations, such as bifunctional zeolite- or metal-organic framework (MOF)-based catalysts that operate under mild conditions, are gaining attention for reducing energy demands and chemical [17].

Membrane-coupled continuous reactors also improve product separation and catalyst stability, though initial investment costs remain high [18]. Thus, synergies between process optimization, supportive policies, and circular economy models are key to transforming WCO into a high-value energy commodity [19]. While several reviews have discussed biodiesel production from WCO or advances in catalysis, few have focused specifically on the integrated strategies of process intensification that combine pretreatment optimization, catalyst innovation, and advanced reactor design. This review addresses that gap by providing a comprehensive analysis of recent advancements in process intensification, including novel heterogeneous and bifunctional catalysts, membrane and microwave-assisted reactors, and circular economy integration strategies. It further emphasizes the importance of standardizing WCO feedstock and developing scalable systems applicable in countries like Indonesia, which produces over 4 million tons of WCO annually. This paper aims not only to synthesize existing knowledge but also to propose future directions for scalable, efficient, and environmentally sound biodiesel production from WCO by aligning technical strategies with economic and policy considerations.

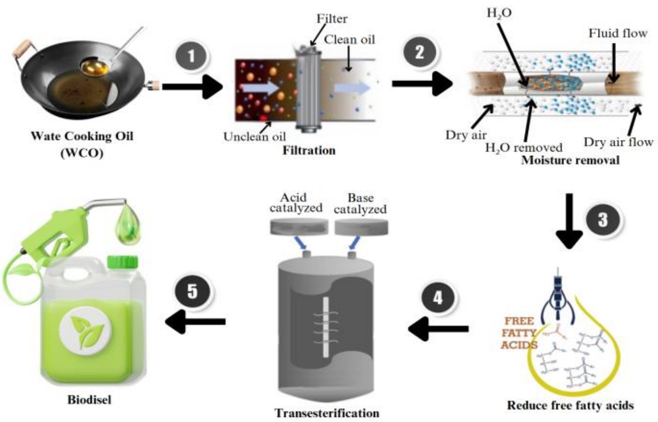

Figure 1. Biodiesel production process from waste cooking oil (WCO) through transesterification steps [20].

A comprehensive schematic in Figure 1 illustrates the chemical reaction pathway of transesterification, the primary process in biodiesel production. Starting with triglycerides (the main components of oils or fats) and an alcohol (e.g., methanol or ethanol), this reaction yields fatty acid methyl esters (FAME), known as biodiesel, and glycerol as a byproduct. The diagram also depicts the typical associated processing steps: from feedstock preparation and the transesterification reaction stage, to the separation of biodiesel product and glycerol purification. The separation process involves washing to remove impurities and byproducts, as well as evaporation/distillation for biodiesel purification and recovery of unreacted alcohol. Glycerol, as a byproduct, also undergoes a purification step for further utilization. This diagram visually elucidates the chemical and operational fundamentals underpinning biodiesel production.

2. Materials and methods

2.1 Research Location and Source of Materials

Used cooking oil is one of the potential feedstocks for biodiesel production that can be utilized in Indonesia. This is evident from the volume of used cooking oil production in the country, which reaches approximately 4,000,000 tons per year [21]. In various studies, waste cooking oil (WCO) is collected from diverse sources such as restaurants [22] and university cafeterias to ensure a variety of feedstock characteristics, which is crucial in evaluating process intensification strategies. Globally, WCO production, especially in highly populated countries, can reach hundreds of millions of tons annually [23]. This indicates that WCO holds significant potential as a sustainable alternative feedstock for biodiesel production Waste cooking oil (WCO) is an economically viable resource, with an annual production of approximately 18.6 million tons. It is collected from diverse sources such as restaurants, food processing industries, fast-food outlets, and households, and is relatively low-cost compared to other oil sources [24]. The heterogeneity of these sources inherently leads to significant variability in WCO's physiochemical properties, including its free fatty acid (FFA) content, moisture levels, unsaponifiable matter, and presence of impurities like food particles and heavy metals [25]. For instance, WCO from restaurants often has higher FFA due to prolonged heating, while household WCO might contain more food debris [26]. Understanding these diverse characteristics is crucial, as they directly influence the selection and effectiveness of pretreatment methods and transesterification processes. The inherent variability necessitates thorough characterization of WCO feedstock prior to its conversion, a critical step that underpins the development and evaluation of robust process intensification strategies. This comprehensive approach ensures that proposed methods can effectively handle real-world WCO quality fluctuations, which is vital for industrial-scale applicability and sustainability.

2.2 Characterization and Pretreatment of Waste Cooking Oil

Before being used in the transesterification process, waste cooking oil must undergo a pretreatment stage to remove physical and chemical contaminants that could reduce biodiesel conversion efficiency [27]. Pretreatment generally begins with filtration using a 300-micron filter cloth to eliminate food residues and solid particles [28]. The next step involves heating the oil to a temperature of 100–110 °C for one hour to reduce its water content, as high moisture levels can lead to saponification when using a base catalyst. Subsequently, the oil is centrifuged at 12,000 rpm for 10 minutes at 30 °C to separate the supernatant phase (clean oil) from the sediment (heavy contaminants) [22]. The supernatant fraction is then used for biodiesel production. Further characterization is performed on the oil to measure its acid value, saponification value, density, and viscosity, which are critical parameters in determining the optimal transesterification operating conditions [29].

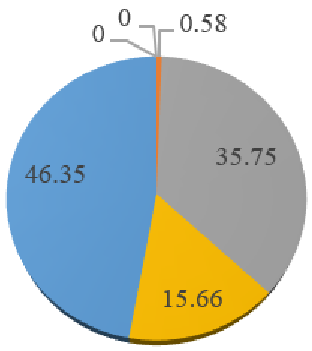

Figure 2. Fatty acid composition of waste cooking oil (WCO) prior to biodiesel production [30].

The fatty acid composition of waste cooking oil (WCO), as shown in Figure 2, indicates that the dominant component is 9-octadecenoic acid (oleic acid) at 46.35%, followed by ethyl oleate at 35.75%, and hexadecanoic acid (palmitic acid) at 15.66%. Additionally, 9-hexadecenoic acid is present at 0.58%, while tetradecanoic acid is not detected. This composition highlights the high content of unsaturated fatty acids in WCO, making it a suitable feedstock for biodiesel production due to its favorable chemical properties.

2.3 Reagents and Catalyst Systems

The efficiency and sustainability of biodiesel production from waste cooking oil (WCO) are critically dependent on the selection of appropriate reagents and catalyst systems for the transesterification process. To provide a comprehensive overview and facilitate a clearer comparison, Table 1 summarizes the key characteristics, advantages, disadvantages, and specific applications of the various reagent and catalyst systems discussed in this section for waste cooking oil (WCO) based biodiesel production.

Table 1. Comparative Evaluation of Catalyst Systems for Biodiesel Production from Waste Cooking Oil (WCO)

Catalyst Type	Examples / Source	Key Characteristics / Advantages	Disadvantages / Challenges	Application for WCO (FFA content)	Sustainability Aspect	Reference
Homogeneous Base	NaOH, KOH	High activity, Fast reaction rates	Soap formation, difficult separation, wastewater generation, corrosion	Low FFA WCO (<0.5 wt%)	Reusability: Low Environmental Impact: Concern	[31]
Homogeneous Acid	H_2SO_4	Highly effective for high-FFA esterification (≥96%)	Corrosive, non-reusable, separation challenges, substantial wastewater	High FFA WCO (>2 wt%)	Reusability: Low Environmental Impact: Concern	[32] [33]
Heterogeneous Base	CaO, MgO, Zeolites, Bone ash,	Easy separation, reusable (≥5 cycles), low-cost (waste-based),	Slower than homogeneous catalysts,	Moderate to low FFA (depending on	Reusability: High Environmental Impact: Low	[34]

	Calcined agricultural ash	eco-friendly, high biodiesel yield (80–98%)	sensitive to moisture	feedstock pretreatment)	treatment, Waste valorization	
Heterogeneous Acid	SO_4^{2-}/ZnO-β-zeolite	Reusable, effective for simultaneous esterification + transesterification, high acidity, large pore size	Reduced performance after multiple cycles (~80% after 3 uses), complex synthesis, Potential leaching	High FFA WCO (>2 wt%)	Reusability: Medium Environmental Impact: Moderate, Potential leaching	[35]
Biocatalysts	Lipase enzymes (*Bacillus stearothermophilus, Staphylococcus aureus*) immobilized on $CaCO_3$	Yield: 97.66 ± 0.57%, No pre-treatment needed, Better stability (retained 93% activity after 6 cycles), Stable after 60 days storage at 4 °C, Operates under mild conditions (55 °C), Minimal byproducts, Complies with EN 14214	High initial cost, Sensitivity to conditions	Broad range (specific conditions), Effective without pre-treatment	Reusability: High Environmental Impact: Benign	[36]
Bifunctional/Multifunctional	Biomass-MOF-derived CaO–ZrO_2	Simultaneous esterification/transesterification; high yield (97.2%); microwave-assisted; optimized by RSM	Complex synthesis; requires statistical optimization	High FFA oils (assumed)	Reusability: High Environmental Impact: Energy-efficient, Biomass-based	[37]

From the findings presented in Table 1, each catalyst type offers distinct benefits and limitations depending on the feedstock characteristics, particularly FFA content. Homogeneous base catalysts such as NaOH and KOH are suitable for low-FFA WCO but pose challenges in terms of separation and environmental waste. Homogeneous acid catalysts like H_2SO_4 are effective for esterifying high-FFA feedstocks but are non-reusable and highly corrosive. In contrast, heterogeneous catalysts—both base and acid types—demonstrate greater sustainability through reusability and ease of separation, with several options now derived from waste materials. Biocatalysts, while environmentally superior, remain limited by their cost and sensitivity to process conditions. Bifunctional and multifunctional catalysts represent a promising frontier by enabling simultaneous esterification and transesterification, thus simplifying the process and reducing energy consumption. Overall, heterogeneous and bifunctional catalysts are more favorable for industrial-scale, sustainable biodiesel production from WCO, especially when aligned with circular economy principles and process intensification strategies.

2.4 Biodiesel Production Process

Transesterification process using homogeneous catalysts are widely employed for mass production because of the requirement of low pressure and temperature conditions and faster conversion rate [38] Biodiesel production from waste cooking oil (WCO) is commonly carried out through transesterification, a chemical process where triglycerides in the oil react with an alcohol—usually methanol—in the presence of a catalyst such as NaOH or CaO to produce biodiesel and glycerol, as illustrated in Figure 3. Before the reaction, the WCO must undergo pretreatment (e.g., filtration and dehydration) to remove impurities and reduce free fatty acid (FFA) content. If the FFA is high, an acid-catalyzed esterification step is performed first. The transesterification typically occurs at around 60°C with constant stirring, followed by separation and purification of the biodiesel to meet quality standards like ASTM D6751 or EN 14214 [39].

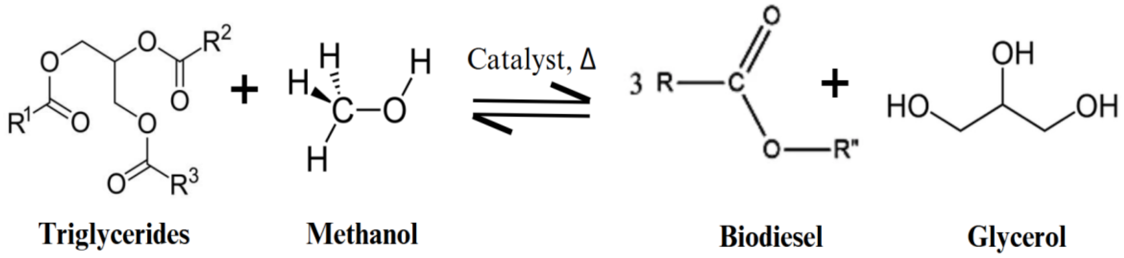

Figure 3. Transesterification of triglycerides with methanol to produce biodiesel and glycerol using a catalyst and heat [40].

2.5 Product Analysis

Transesterification of natural triglycerides, such as oils and fats, is used to produce fatty acid methyl esters (FAME) which are key reagents in the chemical industry and serve as raw materials for the production of long-chain carboxylic acids, detergents, alternative fuels for diesel engines (biodiesel) [41]. The FAME composition of biodiesel can be determined using the gas chromatography method (GC-FID).

Table 2. Comparison of Biodiesel Production Methods from WCO Based on FAME Yield, Viscosity, and Quality Standards

Production Method	FAME Yield (%)	Viscosity (cSt, 40°C)	Quality Standard	Reference
NaOH (homogeneous)	85–90	4,2	ASTM D6751	[38]
CaO (heterogeneous)	88–92	4,5	EN 14214	[42]
Ultrasonic-assisted	92–95	4,4	ASTM D6751	[9]
Microwave-assisted	94–96	4,3	EN 14214	[10]
Mo_7-Zn_3/CaO (heterogeneous)	85-95%	4,5	ASTM D6751 EN 14214	[43]

Based on Table 2, various biodiesel production methods are compared in terms of FAME yield, viscosity, and quality standards. The microwave-assisted method produces the highest FAME yield (94–96%), while all methods meet the ASTM D6751 and EN 14214 standards.

Results and discussion

A comparative analysis of biodiesel production methods from waste cooking oil (WCO), as summarized in Table 2, reveals significant variations in FAME yield, viscosity, and compliance with international quality standards. The microwave-assisted method achieved the highest FAME yield (94–96%), surpassing both the homogeneous catalyst approach (NaOH: 85–90%) and the heterogeneous catalyst method (CaO: 88–92%). The use of a heterogeneous catalyst based on cassava leaves impregnated with KOH was able to produce biodiesel from waste cooking oil with a yield of up to 92.9% and a purity of 97.4% at 64 °C within 2 hours of reaction, indicating high efficiency under moderate conditions [44]. This superior performance is attributed to the rapid and uniform heating provided by microwave radiation, which enhances mass and heat transfer, accelerates reaction kinetics, and reduces energy consumption [10]. The ultrasonic-assisted system also achieved high yields (92–95%), due to the cavitation effect that enhances reactant mixing and shortens reaction time [9]. A schematic representation of this integrated intensification strategy, which combines ultrasonic-assisted and microwave-assisted irradiation to improve transesterification through enhanced mixing, mass transfer, and energy efficiency, is shown in Figure 4 [45]. These findings align with previous studies highlighting the role of process intensification technologies in optimizing transesterification efficiency [7,8].

Table 3. Summary of advantages and challenges of process intensification methods for biodiesel production from WCO.

Method	Advantages	Challenges	Reference
Microwave-assisted	Rapid heating, uniform temperature, high yield, low energy use	High equipment cost, scalability issues	[10]
Ultrasonic-assisted	Enhanced mixing via cavitation, faster reaction time	Equipment fragility, limited large-scale use	[9]
Homogenizer-assisted	Very short reaction time (5 min), energy-saving	Catalyst separation, still under development	[46]

The comparison presented in Table 3 illustrates the key advantages and challenges of various process intensification methods used in biodiesel production from WCO. Microwave-assisted transesterification offers benefits such as rapid and uniform heating, high yield, and low energy consumption; however, it is limited by high equipment costs and scalability issues. Ultrasonic-assisted methods improve mixing efficiency through cavitation and accelerate reaction time, but they suffer from equipment fragility and limited large-scale application. Homogenizer-assisted processes provide very short reaction times and energy savings, although they are still under development and face challenges in catalyst separation. Overall, each method presents a trade-off between efficiency, technical complexity, and industrial feasibility.

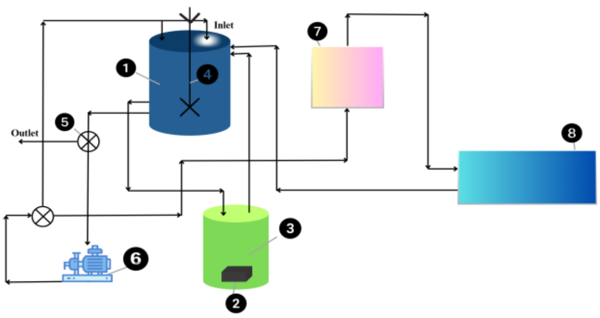

Figure 4. Process schematic of biodiesel synthesis using successive ultrasonic-assisted and microwave-assisted irradiation [45].

The system includes: (1) Oil container, (2) Heater, (3) Water tank, (4) Mixer, (5) Valves, (6) Pump, (7) Ultrasonic-assisted reactor, and (8) Microwave-assisted reactor [45]. This integrated intensification approach enhances transesterification by improving mixing, mass transfer, and energy efficiency. Recent innovations show that homogenizer-assisted amidation followed by NaOH-catalyzed transesterification can yield 91.4% biodisel in just 5 minutes at room temperature, reducing energy use by over 90% compared to conventional methods [46]. This approach is especially effective for high-FFA WCO. Homogeneous catalysts such as NaOH, while efficient, pose challenges including difficult recovery and reuse, soap formation as a side product in the presence of free fatty acids (FFA), extensive washing requirements to remove catalysts and contaminants, and environmental concerns due to waste disposal [47]. The use of industrial waste as an adsorbent achieved up to 89.7% FFA reduction, significantly improving the quality of WCO for biodiesel production [48]. In contrast, heterogeneous catalysts such as CaO and Mo_7-Zn_3/CaO offer advantages over homogeneous catalysts, making them widely used in biodiesel production. These advantages include higher process efficiency, lower corrosiveness, relatively low energy requirements, ease of separation, and reusability over several consecutive cycles. Moreover, these catalysts are suitable for use in continuous flow reactors and generate less and safer wastewater, as they do not require a washing step [49].

The bifunctional catalyst Mo_7-Zn_3/CaO, which can simultaneously perform esterification and transesterification, represents an advancement in catalyst design to address the high FFA content in WCO [31]. Although the viscosity is slightly higher (4.5 cSt) with heterogeneous catalyst methods compared to the microwave-assisted system (4.3 cSt), both still meet ASTM D6751 and EN 14214 standards, indicating no compromise in biodiesel quality [10]. Heterogeneous catalysts offer sustainability and reusability, with up to 95% efficiency in mechanically assisted systems, though performance depends on catalyst loading, alcohol ratio, and reactor type [50]. ZnO nanocatalysts achieved 97% conversion in under 3 hours, though concerns remain about cost and environmental impact [7]. Economic and environmental considerations further reinforce the viability of WCO-based biodiesel [51]. The integration of reusable catalysts and waste-derived feedstocks reduces raw material costs and aligns with the principles of a circular economy [52]. For example, utilizing glycerol as a by-product for the production of bioethanol or other value-added products enhances process sustainability [13]. Life cycle assessment (LCA) confirms that WCO biodiesel reduces greenhouse gas emissions by 60–80% compared to fossil diesel, despite the energy-intensive pretreatment stage [53]. However, challenges such as inconsistent WCO composition, high initial investment costs for advanced reactors (e.g., membrane-coupled systems), and water eutrophication due to energy use must be addressed [40]. Standardizing the quality of used cooking oil through policy interventions and implementing incentives for structured collection systems has been deemed effective in enhancing feedstock reliability for supporting industrial-scale biodiesel technology adoption. A structured and sustainable WCO supply chain is essential to support biodiesel production systems, particularly at the community and regional scales, as illustrated in Figure 5, which presents the integrated flowchart of waste cooking oil (WCO) sourcing, biodiesel production stages, and subsequent waste treatment within a sustainable biofuel production framework.

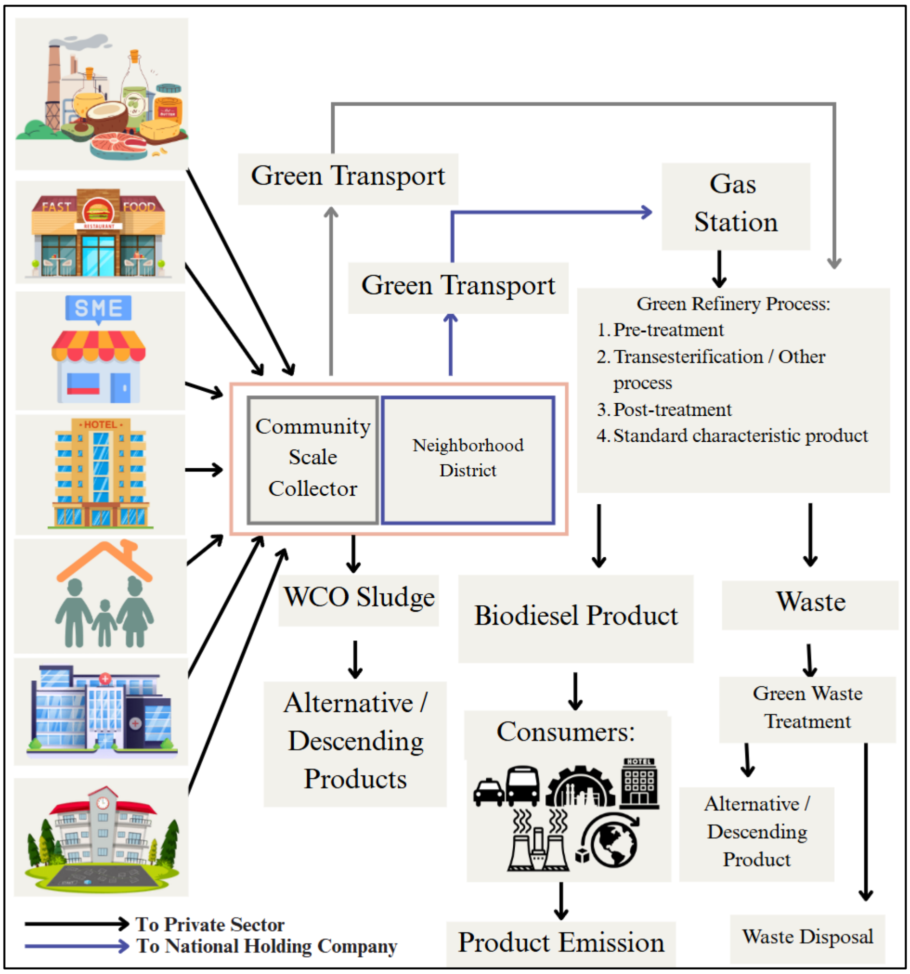

Figure 5. Integrated flowchart of waste cooking oil (WCO) sourcing, biodiesel production stages, and subsequent waste treatment within a sustainable biofuel production framework [54].

This system-oriented approach not only improves feedstock reliability but also supports the integration of circular economy principles, turning waste into valuable energy resources while minimizing environmental impacts. Therefore, although microwave-assisted and ultrasonic-assisted transesterification methods demonstrate high efficiency in biodiesel production from WCO, their industrial-scale application still faces economic and technological challenges. Future research should focus on the development of hybrid systems that integrate process intensification, waste valorization, and policy support to achieve a sustainable bioenergy transition. For instance, developed a reusable, eco-friendly biomass-waste-based heterogeneous catalyst that showed high efficiency in microwave-assisted biodiesel production, while also reducing costs and environmental impacts [55].

Conclusions

The reviewed literature demonstrates that biodiesel production from waste cooking oil (WCO) has advanced significantly through innovations in process intensification, including reactor design, catalyst development, and feedstock pretreatment. While microwave- and ultrasonic-assisted transesterification have consistently achieved higher FAME yields and lower energy inputs, their commercial viability still depends on cost-effective scaling and equipment durability. More than a collection of technical improvements, these findings reveal a broader paradigm shift toward sustainable, circular approaches to biofuel production. Integrating waste-derived heterogeneous catalysts, valorizing glycerol by-products, and applying membrane or hybrid reactors signal the movement beyond linear process design toward closed-loop, resource-efficient systems. Such strategies have implications not only for WCO biodiesel but also for broader bioenergy and waste valorization pathways. Nevertheless, the field still faces notable challenges, particularly in feedstock variability, process standardization, and life cycle environmental trade-offs. Future research should prioritize techno-economic integration, policy alignment, and system-level modeling to support industrial implementation. Furthermore, comparative, data-driven studies under uniform conditions are necessary to generalize best practices across contexts. In conclusion, the synergy between pretreatment methods, catalytic systems, and intensified reactor technologies is critical to achieving sustainable biodiesel production from WCO. By addressing existing technical and economic barriers through an integrated, multidisciplinary lens, the transition from laboratory-scale innovation to industrial sustainability can be more effectively realized.

References

[1] T. Alex-Oke, O. Bamisile, D. Cai, H. Adun, C. C. Ukwuoma, S. A. Tenebe, and Q. Huang, "Renewable energy market in Africa: Opportunities, progress, challenges, and future prospects," *Energy Strateg. Rev.*, vol. 59, no. February, p. 101700, 2025.

[2] S. M. Farouk, A. M. Tayeb, S. M. S. Abdel-Hamid, and R. M. Osman, "Recent advances in transesterification for sustainable biodiesel production, challenges, and prospects: a comprehensive review," *Environ. Sci. Pollut. Res.*, vol. 31, no. 9, pp. 12722–12747, 2024.

[3] H. H. Naseef and R. H. Tulaimat, "*Transesterification and esterification for biodiesel production: A comprehensive review of catalysts and palm oil feedstocks*," vol. 26, no. February. Elsevier Ltd, 2025.

[4] J. Jayaprabakar, S. S. Dawn, M. Anish, J. Giri, K. Sudhakar, A. A. Alarfaj, and A. Guru, "Development of Free Fatty Acid (FFA) monitoring device for evaluation of oil samples used for biodiesel production," *Heliyon*, vol. 10, no. 17, p. e37118, 2024.

[5] T. Irawan, "Variation of the Chemical Composition of Waste Cooking Oils upon Bentonite Filtration," vol. 6, no. 1, pp. 53–62, 2022.

[6] B. T. Asfaw, M. T. Gari, and M. Jayakumar, "Transesterification of biodiesel from non-edible oils using heterogeneous base catalysts: A comprehensive review of potential renewable biomass feedstocks," *Chem. Eng. J.*, vol. 511, no. December 2024, p. 162028, 2025.

[7] R. Jayabar, "Advancements in catalysts, process intensification, and feedstock utilization for sustainable biodiesel production," *Results Eng.*, vol. 24, no. October, p. 103668, 2024.

[8] I. Tariq, M. Zubair, W. Iqbal, A. Badshah, S. M. Abbas, and A. Haider, "Alkaline earth metal oxides supported on WO3@MCM-41; bifunctional catalysts for biodiesel production from corn and waste cooking oil," *Hybrid Adv.*, vol. 10, no. April, p. 100477, 2025.

[9] M. A. G. Nasim, O. Khan, M. Parvez, and B. K. Bhatt, "Optimizing ultrasonic reactor operating variables using intelligent soft computing models for increased biodiesel production," *Green Technol. Sustain.*, vol. 1, no. 3, p. 100033, 2023.

[10] K. Subramaniam, K. Y. Wong, K. H. Wong, C. T. Chong, and J. H. Ng, "Enhancing Biodiesel Production: A Review of Microchannel Reactor Technologies," *Energies*, vol. 17, no. 7, 2024.

[11] N. A. M. Aziz, R. Yunus, D. Kania, and H. A. Hamid, "Prospects and challenges of microwave-combined technology for biodiesel and biolubricant production through a transesterification: A review," *Molecules*, vol. 26, no. 4, 2021.

[12] W. M. Kedir, K. T. Wondimu, and G. S. Weldegrum, "Optimization and characterization of biodiesel from waste cooking oil using modified CaO catalyst derived from snail shell, "*Heliyon*, vol. 9, no. 5, p. e16475, 2023.

[13] M. Elsayed, M. Eraky, A. I. Osman, J. Wang, M. Farghali, A. K. Rashwan, I. H. Yacoub, D. Hanelt, and A. Abomohra, "Sustainable valorization of waste glycerol into bioethanol and biodiesel through biocircular approaches: a review," *Environ. Chem. Lett.*, vol. 22, no. 2, pp. 609–634, 2024.

[14] S. Foteinis, E. Chatzisymeon, A. Litinas, and T. Tsoutsos, "Used-cooking-oil biodiesel: Life cycle assessment and comparison with first- and third-generation biofuel," *Renew. Energy*, vol. 153, pp. 588–600, 2020.

[15] Z. Elahi, F. M. Jakarni, R. Muniandy, S. Hassim, M. S. Ab Razak, A. H. Ansari, and M. M. B. Zair, "Waste cooking oil as a sustainable bio modifier for asphalt modification: A review," *Sustain.*, vol. 13, no. 20, pp. 1–27, 2021.

[16] T. Zheng, B. Wang, M. A. Rajaeifar, O. Heidrich, J. Zheng, Y. Liang, and H. Zhang, "How government policies can make waste cooking oil-to-biodiesel supply chains more efficient and sustainable," *J. Clean. Prod.*, vol. 263, p. 121494, 2020.

[17] T. Derbe, E. A. Zereffa, T. Sani, and T. Girma, "Synthesis of Green Heterogeneous Bifunctional

Zeolite-A/Biochar Catalyst for the Production of Biodiesel from Waste Cooking Oil," *Catal. Letters*, pp. 5530–5545, 2024.
[18] S. Nong, M. Wang, X. Wang, Y. Li, S. Yu, C. Tang, G. Li, and L. Xu,"A multifunctional guanosine-based carbon dots for dead microbial imaging and synergistic broad-spectrum antimicrobial therapy," *Chem. Eng. J.*, vol. 485, no. December 2023, 2024.
[19] S. Zhu, C. Zhang, X. Fang, Y. Yan, X. Hang, Y. Chen, L. Sun, X. Xie, and Y. Li,"The spatiotemporal patterns and climate impacts of the carbon dynamics in economically developed areas of China during the past 40 years: A case of Jiangsu Province," *J. Clean. Prod.*, vol. 435, no. December 2023, p. 140567, 2024.
[20] A. I. Osman, M. Nasr, M. Farghali, A. K. Rashwan, A. Abdelkader, A. H. Al-Muhtaseb, I. Ihara, and D. W. Rooney, "Optimizing biodiesel production from waste with computational chemistry, machine learning and policy insights*: a review*, " vol. 22, no. 3. Springer International Publishing, 2024.
[21] B. Haryanto, R. Tambun, O. M. Sitohang, S. Y. Sidauruk, G. E. Naomi, and V. Alexander, "Competence of corncob (Zea mays L.) powder with HCl activation as adsorbent to purify waste cooking oil: Reference in the batch adsorption process," *South African J. Chem. Eng.*, vol. 52, no. August 2024, pp. 48–60, 2025.
[22] R. Nabizadeh, I. L. García, Z. Bahmani, A. Norouzian Baghani, S. Sadjadi, K. Yaghmaeian, B. Kamarehie, A. H. Mahvi, and M. Yunesian, "Energy and cost analysis of bottom waste cooking oil (B-WCO) based solid alcohol biofuel and supernatant waste cooking oil (S-WCO) based biodiesel," *Heliyon*, vol. 11, no. 4, p. e42180, 2025.
[23] J. Martín-Gonz´alez, J.-F. Montero-Bull´on, G. Mu˜noz-Fern´andez, R. M. Buey, and A. Jim´enez, "Valorization of waste cooking oil for bioproduction of industrially-relevant metabolites in Ashbya gossypii," *N. Biotechnol.*, vol. 88, no. November 2024, pp. 32–38, 2025.
[24] L. Li, L. Li, J. Ma, and F. Xie, "Biodiesel production from the transesterification of waste cooking oil via CaO/HAP/MnFe@K magnetic nanocatalyst derived from eggshells and chicken bones: Diesel engine and kinetic studies," *Renew. Energy*, vol. 237, no. October, 2024.
[25] S. Suherman, I. Abdullah, M. Sabri, and A. S. Silitonga, "Evaluation of Physicochemical Properties Composite Biodiesel from Waste Cooking Oil and Schleichera oleosa Oil," *Energies*, vol. 16, no. 15, pp. 1–20, 2023.
[26] P. Sharma, M. Usman, E. S. Salama, M. Redina, N. Thakur, and X. Li, "Evaluation of various waste cooking oils for biodiesel production: A comprehensive analysis of feedstock," *Waste Manag.*, vol. 136, no. October, pp. 219–229, 2021.
[27] C. G. Lopresto, M. G. De Paola, and V. Calabrò, "Importance of the properties, collection, and storage of waste cooking oils to produce high-quality biodiesel – An overview," *Biomass and Bioenergy*, vol. 189, no. August, 2024.
[28] Suherman, Ilmi, M. Sabri, E. F. Ginting, and J. J. Silalahi, "Biodiesel production of WCO-neem oil and mixed using pilot plant scale with ultrasound and overhead stirred and characteristic of emissions in fire tube boiler," *Case Stud. Chem. Environ. Eng.*, vol. 11, no. November 2024, p. 101029, 2025.
[29] M. U. H. Suzihaque, N. Syazwina, H. Alwi, U. K. Ibrahim, S. Abdullah, and N. Haron, "A sustainability study of the processing of kitchen waste as a potential source of biofuel: Biodiesel production from waste cooking oil (WCO)," *Mater. Today Proc.*, vol. 63, pp. S484–S489, 2022..
[30] A. S. Shahsamandy, M. Alae, and F. Xiao, "Harnessing waste materials for aged asphalt binder revitalization through investigation of rejuvenation mechanism and performance enhancement," *J. Clean. Prod.*, vol. 493, no. January, p. 144972, 2025.
[31] V. Mandari and S. K. Devarai, "Biodiesel Production Using Homogeneous, Heterogeneous, and Enzyme Catalysts via Transesterification and Esterification Reactions: a Critical Review," *Bioenergy Res.*, vol. 15, no. 2, pp. 935–961, 2022.
[32] M. Supeno, J. P. Sihotang, Y. V. Panjaitan, D. S. Y. Damanik, J. B. Tarigan, and E. K. Sitepu, "Room temperature esterification of high-free fatty acid feedstock into biodiesel," *RSC Adv.*, vol. 13, no. 47, pp. 33107–33113, 2023.
[33] P. Juera-Ong, K. Pongraktham, Y. M. Oo, and K. Somnuk, "Reduction in Free Fatty Acid Concentration in Sludge Palm Oil Using Heterogeneous and Homogeneous Catalysis: Process Optimization, and Reusable Heterogeneous Catalysts," *Catalysts*, vol. 12, no. 9, 2022.
[34] C. T. Oloyede, S. O. Jekayinfa, A. O. Alade, O. Ogunkunle, N. A. U. Otung, and O. T. Laseinde, "Exploration of agricultural residue ash as a solid green heterogeneous base catalyst for biodiesel production," *Eng. Reports*, vol. 5, no. 1, pp. 1–23, 2023.
[35] B. O. Yusuf, S. A. Oladepo, and S. A. Ganiyu, "Biodiesel Production from Waste Cooking Oil via

β-Zeolite-Supported Sulfated Metal Oxide Catalyst Systems," *ACS Omega*, vol. 8, no. 26, pp. 23720–23732, 2023.

[36] A. Ben Bacha, M. Alonazi, M. G. Alharbi, H. Horchani, and I. Ben Abdelmalek, "Biodiesel Production by Single and Mixed Immobilized Lipases Using Waste Cooking Oil," *Molecules*, vol. 27, no. 24, pp. 1–14, 2022.

[37] S. P. Gouda, J. M. Jasha, P. Kumar, A. Dhakshinamoorthy, U. Rashid, and S. L. Rokhum, "Microwave-Assisted Biodiesel Production Using UiO-66 MOF Derived Nanocatalyst: Process Optimization Using Response Surface Methodology," *Catalysts*, vol. 12, no. 11, 2022.

[38] W. R. Singh and H. N. Singh, "Maximizing waste cooking oil biodiesel production employing novel Brotia costula derived catalyst through statistical and machine learning optimization techniques," *Mater. Today Commun.*, vol. 41, no. October, 2024.

[39] O. Awogbemi and D. A. Desai, "Application of computational technologies for transesterification of waste cooking oil into biodiesel," *Biomass and Bioenergy*, vol. 194, no. January, p. 107620, 2025.

[40] M. Cerón Ferrusca, R. Romero, S. L. Martínez, A. Ramírez-Serrano, and R. Natividad, "Biodiesel Production from Waste Cooking Oil: A Perspective on Catalytic Processes," *Processes*, vol. 11, no. 7, 2023.

[41] M. Salaheldeen, A. A. Mariod, M. K. Aroua, S. M. A. Rahman, M. E. M. Soudagar, and I. M. R. Fattah, "Current state and perspectives on transesterification of triglycerides for biodiesel production," *Catalysts*, vol. 11, no. 9, pp. 1–37, 2021.

[42] I. Tariq, M. Zubair, W. Iqbal, A. Badshah, S. M. Abbas, and A. Haider, "Alkaline earth metal oxides supported on WO3@MCM-41; bifunctional catalysts for biodiesel production from corn and waste cooking oil," *Hybrid Adv.*, vol. 10, no. December 2024, p. 100477, 2025.

[43] S. Kouider Elouahed, N. Asikin-Mijan, A. G. Alsultan, O. Kaddour, M. R. Yusop, H. Mimoun, S. Samidin, N. Mansir, and Y. H. Taufiq-Yap, "Optimization of the activity of Mo7-Zn3/CaO catalyst in the transesterification of waste cooking oil into sustainable biodiesel via response surface methodology," *Energy Convers. Manag.*, vol. 303, no. November 2023, p. 118185, 2024.

[44] A. O. Barata, A. S. Reshad, M. Abewaa, and Gnaro, "Synthesis and characterization of potassium hydroxide impregnated cassava leaves heterogeneous catalyst for biodiesel production from waste cooking oil," *J. Mol. Liq.*, p. 111985, 2025.

[45] Y. D. Bizualem and A. G. Nurie, "A review on recent biodiesel intensification process through cavitation and microwave reactors: Yield, energy, and economic analysis," *Heliyon*, vol. 10, no. 2, p. e24643, 2024.

[46] J. B. Tarigan, B. Ginting, S. Perangin-angin, R. N. Sari, P. F. Sianipar, and E. K. Sitepu, "Homogenizer-intensified amidation of free fatty acids in waste cooking oil for biodiesel production," *South African J. Chem. Eng.*, vol. 46, no. August, pp. 271–276, 2023.

[47] A. A. Abdelrahman and M. A. Abo El-Khair, "Advanced Biodiesel Production: Feedstocks, Technologies, Catalysts, Challenges, and Environmental Impacts," *J. Environ. Chem. Eng.*, vol. 13, no. 1, p. 114966, 2025.

[48] C. G. Lopresto, M. Gentile, A. Caravella, S. Candamano, and V. Calabrò, "De-acidification of waste cooking oils by adsorption on industrial waste: Kinetic analysis of a green pretreatment for biodiesel production," *Chemosphere*, vol. 380, no. February, 2025.

[49] M. Ansari, H. Jamali, R. Ghanbari, M. H. Ehrampoush, P. Zamani, and B. Hatami, "Heterogeneous solid acid catalysts for sustainable biodiesel production from wastewater-derived sludge: A systematic and critical review," *Chem. Eng. J. Adv.*, vol. 22, no. February, p. 100718, 2025.

[50] Monika, S. Banga, and V. V. Pathak, "Biodiesel production from waste cooking oil: A comprehensive review on the application of heterogenous catalysts," *Energy Nexus*, vol. 10, no. May, p. 100209, 2023.

[51] Y. Zhao, C. Wang, L. Zhang, Y. Chang, and Y. Hao, "Converting waste cooking oil to biodiesel in China: Environmental impacts and economic feasibility," *Renew. Sustain. Energy Rev.*, vol. 140, no. December 2019, p. 110661, 2021.

[52] S. Elias, A. M. Rabiu, B. I. Okeleye, V. Okudoh, and O. Oyekola, "Bifunctional heterogeneous catalyst for biodiesel production from waste vegetable oil," *Appl. Sci.*, vol. 10, no. 9, 2020.

[53] Z. Hu, J. Shen, P. Tan, and D. Lou, "Life cycle carbon footprint of biodiesel production from waste cooking oil based on survey data in Shanghai, China," *Energy*, vol. 320, no. December 2024, p. 135318, 2025.

[54] A. Rahman , M.A.M. Oktaufik, T. W. Sasongko, I. Guntoro, D. Soedjati, N. Abbas, A. Rahman, F. Ulfah, A. Widiarto, S. Siswanto, D. Dharmawan, S. E. Yuwono Trihadi, K. Kusretuwardani, A. L. Prihatin, A. Hadi, S. Indrijarso, P. Rahardjo, A. Barkah, I. Febijanto, and N. A. Sasongko "Current

scenario and potential of waste cooking oil as a feedstock for biodiesel production in Indonesia: Life cycle sustainability assessment (LCSA) review," *Case Stud. Chem. Environ. Eng.*, vol. 11, no. December 2024, p. 101067, 2025

[55] G. Yadav, N. Yadav, and M. Ahmaruzzaman, "Microwave-assisted synthesis of biodiesel by a green carbon-based heterogeneous catalyst derived from areca nut husk by one-pot hydrothermal carbonization," *Sci. Rep.*, vol. 12, no. 1, pp. 1–14, 2022.