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## Advances in Catalysts for Biodiesel Production: A Systematic Review of Trends, Challenges, and Future Prospects

Okpo Samson Onoriode<sup>1\*</sup>, Ibeh Mark Chijioke<sup>2</sup>

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### ABSTRACT

Biodiesel has attracted worldwide interest as an alternative renewable fuel source to fossil fuels, but its industrial applications are limited to catalytic inefficiencies, high costs of production, and environmental trade-offs. This review summarizes the gains in catalyst development and process integration and aims to determine new trends, compare performance of different classes of catalysts, and provide a roadmap to sustainable adoption in industry. Scopus, Web of Science, and ScienceDirect were utilized to conduct a systematic review of peer-reviewed studies published between 2015 and 2025, covering both the historical milestones and the latest innovations. It is found that there is a strong transition between traditional homogeneous and heterogeneous heterogeneous systems and sophisticated nanocatalysts, bifunctional systems, MOFs, COFs, and biochar systems, which present varying benefits to activity, selectivity, and recyclability but remain at a disadvantage due to deactivation, feedstock effects, and bottlenecks in mass transfer. Ultrasound-assisted systems and microreactors have also facilitated intensifying reactions, whereas artificial intelligence (AI) and machine learning (ML) have made it possible to predictatively model catalyst performance, feedstock oscillations, and yield optimization. Regardless of these developments, high feedstock prices, techno-economic uncertainties, and life-cycle environmental issues still present a critical obstacle. In the future, the integration of hybrid catalysts, circular biorefinery, digital approaches, and facilitating policy frameworks will prove pivotal towards scaling the biodiesel production. Together, these avenues will make biodiesel not just a renewable transportation resource but also a key pillar of the circular bioeconomy and the global energy transition towards low-carbon.

### INTRODUCTION

Biodiesel is a potential renewable energy source because it is biodegradable, produces fewer greenhouse gases, and can be used in existing diesel systems (Rehman *et al.*, 2021; Thangaraj *et al.*, 2019). By 2031, global production is forecasted to reach over 55 billion liters, and Asia is one of the significant growth areas (IFPRI, 2022; Rashid *et al.*, 2025). To fulfill this demand, low-cost feedstocks including waste cooking oil, animal fats, and non-edible oils, and high-efficiency, low-cost, and sustainable catalysts are necessary (Bhan *et al.*, 2025; Ghosh *et al.*, 2024). Bulk homogeneous catalysts dominate in industry, but have separation and waste water issues (Atadashi *et al.*, 2013; Semwal *et al.*, 2011). Nanostructured, heterogeneous, and enzymatic systems have been developed to circumvent some of these drawbacks but face barriers as such as cost and stability (Rajak *et al.*, 2025; Rathod *et al.*, 2023). Other novel methods are one-pot, bifunctional, and waste-based catalysts and AI/ML driven designs (Sulaiman *et al.*, 2025b; Yahya *et al.*, 2025). This survey is an overview of the developments, challenges and prospects of biodiesel catalysis, especially focusing on how catalysts are classified according to their synthesis methods, catalytic activity, and durability. It compares the merits and demerits of systems in terms of yield, reusability, and adaptability to multiple feedstock types,

and environmental impact. Furthermore, it reveals new tendencies, such as artificial intelligence (AI), machine learning (ML) and process intensification in the design and optimization of catalysts. The current review is peculiar in its systemic incorporation of developments involving both the traditional homogeneous and heterogeneous types of catalysts, and always toward nanocatalysts, bifunctional catalysts, metal-organic frameworks (MOFs), covalent organic frameworks (COFs) and bioschar-based catalysts. Moreover, it implements recent achievements in process intensification and digitalization process, such as artificial intelligence, machine learning, and digital twin technologies. The article provides a thorough body of knowledge by presenting the comparative framework that evaluates yield performance, reusability, feedstock adaptability, and environmental implication which has never been present in other reviews that could often engage only single catalyst classes or short time timeframes. Furthermore, it identifies gaps that have not been solved yet, including catalyst deactivation, cost-efficient and scalable synthesis pathways, techno-economic, and environmental trade-offs, and connects the unaddressed gaps to the future perspectives of hybrid catalysts, circular biorefineries (Okirie *et al.*, 2025), and supportive policy frameworks. Overall, this review does not only provide a synthesis of existing evidence but it

<sup>1</sup> Department of Chemical Engineering, Southern Delta University, Ozoro, Nigeria

<sup>2</sup> Department of Safety, Health and Environment, University of Salford, Salford, United Kingdom

\* Corresponding author's e-mail: [okpos@dsust.edu.ng](mailto:okpos@dsust.edu.ng)

also sheds light on various avenues to overcome existing bottlenecks and hence provide the tangible information to the required stakeholders in the research community as well as industries regarding ways to advance biodiesel production towards sustainable commercialization.

## LITERATURE REVIEW

### Fundamentals of Biodiesel Production

Biodiesel is produced by converting lipid-based feedstocks into fatty acid alkyl esters via catalysts (Gautam, 2025; Larimi *et al.*, 2024; Ismael *et al.*, 2024). Transesterification involves triglycerides reacting with alcohol, usually methanol, to yield biodiesel and glycerol (Ismael *et al.*, 2024; Tabatabaei *et al.*, 2019). Esterification transforms the free fatty acids (FFAs) to esters, making

it possible to reduce the formation of the soap (Rezki *et al.*, 2024; Zhang *et al.*, 2019b). Reaction kinetics vary with the type of catalyst and reaction temperature, the ratio of alcohol to oil, and the intensity of mixing (Hazrat *et al.*, 2022). The types of feedstocks are; edible oils, non-edible oils, waste cooking oil (WCO) and animal fats, all of which have an impact on catalyst selection and achieve (Sreelekha *et al.*, 2024; Kokkinos *et al.*, 2022). Base catalysts can be used whenever using low-FFA oils, whereas acid catalysts, or two-step procedures involving esterification-transesterification, are required with base catalysts (Javed *et al.*, 2022; Gautam, 2025). The choice of catalyst is, therefore, quite feedstock-specific (Navin *et al.*, 2024; Wang *et al.*, 2023). Figure 1 by Kosuru *et al.* (2024) depicted biodiesel production process.

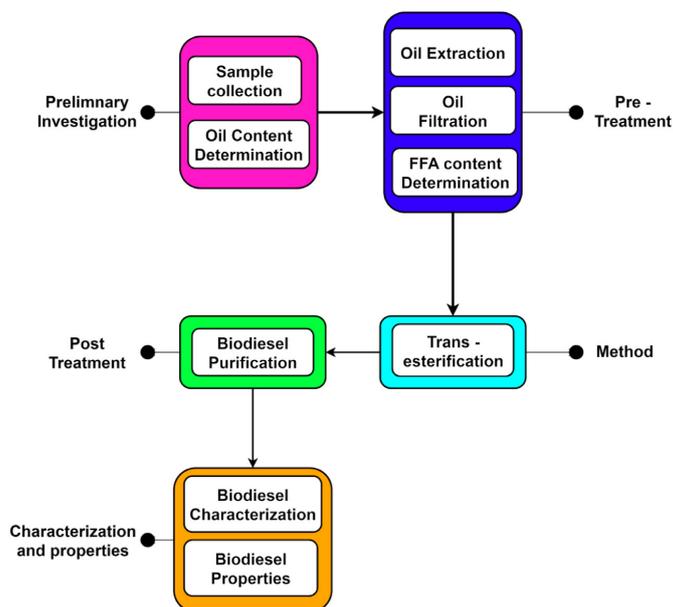


Figure 1: Flowchart for biodiesel production (Kosuru *et al.*, 2024)

## MATERIALS AND METHODS

The systematic review conducted herein aimed to evaluate the progress in catalysts related to biodiesel production. Thorough literature search was carried out on Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley, Taylor & Francis, ACS, RSC, MDPI, Semantic Scholar, Google Scholar, and ResearchGate. The keywords and Boolean operators used to query the database included publications published between 2007 and 2025, including biodiesel production, catalyst, homogeneous, heterogeneous, enzymatic, nanocatalyst, bifunctional, metalorganic framework (MOF), and covalent organic framework (COF). Inclusion criteria required peer-reviewed articles that documented empirical data relating to catalyst synthesis, product yield, reusability, scalability, or environmental effects in any language. The exclusion criteria included non-scientific reports, editorials, duplicates, and publications unsupported by experimental or modeling content. After determination of these criteria, 189 publications were qualified to be analyzed in-depth. Extracted data included catalyst source, feedstock

type, reaction parameters, yields, reusability, scaling, and environmental/techno-economic outcomes.

## RESULTS AND DISCUSSION

### Catalyst Development for Biodiesel

#### Homogeneous Catalysts

Homogeneous catalysts including the alkaline ones, like NaOH and KOH, and the acidic agents, such as H<sub>2</sub>SO<sub>4</sub>, have been used in the production of biodiesel since they are highly active and have the ability to produce high yields in very short time (Bhan *et al.*, 2025). These catalysts work at rather mild reaction conditions and can perform simultaneous transesterification and esterification reactions with each other, which contributes to all the versatility (Gadore *et al.*, 2023). In spite of these advantages, such homogeneous catalysts have significant disadvantages. The easy separation and reuse of a uniform species are also troublesome because they often cause contamination of the product and exclude the possibility of catalyst re-use (Rajak *et al.*, 2025; Maroa & Inambao, 2021). In addition, the purification steps required frequently demand large

amounts of water thus causing a lot of wastewater; simple catalysts are also frustratingly compromised by water and free fatty acids (Gadore *et al.*, 2023). However, the negative environmental implications and operating challenges involving homogeneous catalysts have generated an increasingly sustained interest in alternative heterogeneous catalysts that could yield greater sustainability over time, even though it has been shown that homogeneous catalysts are also effective (Rajak *et al.*, 2025).

### Heterogeneous Catalysts

Heterogeneous catalysts have become key alternatives to their homogeneous counterparts largely because of their robust physical operations and ability to control the processes. Here, it is important to note that they support both batch and continuous-flow reactor modes, streamline downstream separation and purification processes, and generally afford streamlined recovery and reuse (Hua *et al.*, 2025; Rathod *et al.*, 2023; Wang *et al.*, 2023). In addition to these practical advantages, only heterogeneous systems can support concurrent transesterification and esterification pathways, and are

less sensitive to water or free fatty acids that frequently hinder homogeneous media (Bhan *et al.*, 2025; Gadore *et al.*, 2023). The physicochemical properties of these solid acids are inherently connected to both their physicochemical properties: surface area, pore structure, intrinsic acidity, and thermal stability, which together determine the activity, selectivity, and recyclability (Hua *et al.*, 2025). However, the heterogeneous catalysts are often characterised by worse conversion efficiencies compared to their homogeneous counterparts, a drawback that can be largely explained by the mass-transfer constraints that slow down the overall reaction rate (Ogundele, 2025; Gadore *et al.*, 2023). A strategic adjustment of catalyst architecture has been sought to overcome these challenges. This implies intelligent choice and design of active constituents (e.g., metal complexes, nanoparticles) and customized supports including carbonaceous support, metal oxides, and metal-organic frameworks (MOFs), increasing catalytic activity, longevity, and selectivity (Rathod *et al.*, 2023). Table 1 summarizes representative heterogeneous catalysts and their biodiesel yields reported in literatures.

**Table 1:** Some reported heterogeneous catalysts and their biodiesel yields

Feedstock	Catalyst source	Catalyst	Yield (%)	Reference
Waste cooking oil	Avocado seeds	Bifunctional with zinc oxide(ZnO) and Cerium oxide (Ce-O) bond	99.6	Akream <i>et al.</i> ,(2024)
Sunflower oil	Salmon bones	KOH/SFB	99.13	Mohebolkhames <i>et al.</i> , (2024)
UCO	Eggshells-chicken bones	CaO/HAp/MnFe@K nanocatalyst	99.1	Li <i>et al.</i> , (2024)
Argemone Mexicana oil	Chicken eggshells	CaO	99.07	Ashine <i>et al.</i> , (2023)
Carica papaya seed oil	Corn pod	CaO/K <sub>2</sub> O/SiO <sub>2</sub>	99.06	Nyorere <i>et al.</i> (2024)
Used palm cooking oil(UPCO)	Corn pod	CaO/K <sub>2</sub> O/SiO <sub>2</sub>	99.06	Novita <i>et al.</i> (2024)
Glycerol and Acetic Acid	Corn pod	CaO/K <sub>2</sub> O/SiO <sub>2</sub>	99.06	Chakraborty <i>et al.</i> (2016)
Sandbox oil	Sandbox seed shells	Calcined sandbox shell ash-CSSA catalyst- K/Ca/Mg	98.27	Betiku <i>et al.</i> (2024)
Flaxseed oil	Orange-bananna peel	CaO (COB catalyst)	98.78	Rajak <i>et al.</i> (2024)
Dairy waste oil	Rice husk	Cuo/RHA	97.42	Maleki <i>et al.</i> (2024)
Oleic acid	Rice husk	Rice husk sulfonated solid acid catalyst	99.60	Yadav <i>et al.</i> (2023)
Soyabean oil	Murici seeds	CoFe <sub>2</sub> O <sub>4</sub> /Na <sub>2</sub> SiO <sub>3</sub>	97.11	Ribeiro <i>et al.</i> (2024)

### Biocatalysts

Biocatalysts, in particular lipases, offer an environmentally friendly alternative to chemical catalysts for the production of biodiesel (Omolade *et al.*, 2022; Amini *et al.*, 2017). Lipase-catalyzed transesterification works under mild conditions with high substrate specificity. This reduces by-product formation and lessens environmental impact (Hwang *et al.*, 2014; Tan *et al.*, 2010; Tan *et al.*, 2023).

Progress in protein engineering has also improved lipase stability and activity, making enzymatic catalysis more competitive (Tan *et al.*, 2023). Moreover, immobilised lipase systems allow for the continuous production of biodiesel, reducing the loss of enzymes and increasing the efficiency of the process (Tan *et al.*, 2010). Despite these benefits, problems remain. Limited enzyme stability under operational conditions, lower catalytic activity, and high

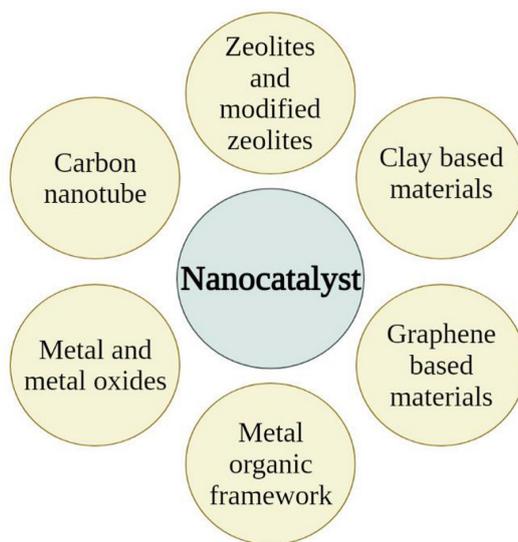
production costs still block large-scale commercialization (Rathod *et al.*, 2023; Bhan *et al.*, 2025). However, ongoing work in enzyme immobilization and genetic engineering offers promising ways to improve both performance and cost-effectiveness.

### Nanocatalysts

Nanocatalysts have become the prospects to biodiesel production because of their high surface-area-volume ratios, controllable physicochemical features, and

selectivity to reactions in transesterification (Asaad *et al.*, 2023; Awogbemi *et al.*, 2024; Gadore *et al.*, 2023; Bhan *et al.*, 2025). They can be formed out of a variety of materials, some of which include zeolites, clay-based materials, graphene-based nanostructures, metal-organic frameworks (MOFs), elemental metals, metal oxides, and carbon nanotubes as demonstrated in Figure 2 (Pandit *et al.*, 2023).

The catalysts can recover and perform more efficiently because catalysts such as copper(II) oxide (CuO),



**Figure 2:** Materials used in nanocatalysis synthesis (Pandit *et al.*, 2023).

iron(III) oxide ( $\text{Fe}_2\text{O}_3$ ) and biochar/ $\text{Fe}_3\text{O}_4$ -based (biosensor) composites are nanostructured and have high catalytic potential, reusability, and magnetism (Awogbemi *et al.*, 2024; Bhan *et al.*, 2025; Li & Liang, 2024). Their nanoscale composition gives a significantly increased ratio of surface to volume, thus enhancing the speed of the reaction and selectivity (Gadore *et al.*, 2023). However, there still is a problem in the production of catalysts, their stability, and recovery, and the hope of exploiting fully the potential of the nanocatalysts in the production of sustainable biodiesel resides in the ability to overcome the challenges in catalyst production combined with surface modification methods (Asaad *et al.*, 2023).

### Emerging Catalysts

The evolution of catalysts in the production of bio-diesel has been through specific stages due to the increasing demand of efficiency, environmental friendliness and sustainability. Homogeneous catalysts like sodium hydroxide (NaOH), potassium hydroxide (KOH) and sodium methoxide were the dominant reagents used in the production of biodiesel in the 1990s. Although very efficient and reactive, these catalysts were characterized by challenging separation, exaggerated wastewater formation, and the lack of reuse, which made them unsustainable at large scale (Sulaiman *et al.*, 2025b; Bahkali *et al.*, 2024). In the 2000s, the focus was switched on heterogeneous catalysts, such as CaO, MgO,  $\text{TiO}_2$ , zeolites, and sulfated

zirconia. They were easy to recover and use again, but of lower conversion efficiency compared to strictly homogeneous systems (Rajak *et al.*, 2025; Ghosh *et al.*, 2024; Gadore *et al.*, 2023). The 2010s came as a year of the discovery of nanocatalysts such as nano-CaO, ZnO nanoparticles, the  $\text{Fe}_3\text{O}_4$  and nanoparticles entirely made out of carbon. Their tunability and large surface area continued to provide enhanced conditions in the activity of the catalyst, stability, and reusability (Bhan *et al.*, 2025; Lakhani *et al.*, 2024; Joshi *et al.*, 2023). In the age of the 2020s, the development of catalysts has become more advanced and now focuses on waste-based catalysts, bifunctionalized systems, biochar station, and designer-based catalysts including MOFs and COFs, as well as artificial intelligence (AI)-based optimization approaches to biodiesel production (Awogbemi *et al.*, 2024; Jacinta *et al.*, 2024; Garg *et al.*, 2023; Tamoradi *et al.*, 2022).

### Bifunctional Catalysts

Bifunctional catalysts, which have both acidic and basic sites, have become more promising materials in the production of biodiesel because they can catalyze both esterification and transesterification, thus processing feedstocks with high free fatty acid (FFA) content efficiently (Changmai *et al.*, 2023; Wang *et al.*, 2023; Munyentwali *et al.*, 2022; Elias *et al.*, 2020). Metal oxides, mixed metal oxides, modified zeolites, and biowaste-derived catalysts are reported (Dai *et al.*, 2021; Al-

Saadi *et al.*, 2020; Chang *et al.*, 2014; Oni-Adimabua *et al.*, 2024). They can be niobium–alkali metal oxide composites (Dai *et al.*, 2021), SrO-ZnO/Al<sub>2</sub>O<sub>3</sub> formed through wet impregnation (Al-Saadi *et al.*, 2020), palm leaf residue-based magnetic hydrochar catalysts (Aliyu *et al.*, 2025), and Fe<sub>3</sub>O<sub>4</sub>-Cs<sub>2</sub>O nanocatalysts prepared by co-precipitation (Ramasamy *et al.*, 2023). They have high-FFA tolerance, no pretreatment is required, dual-site activity, which enhances efficiency, can be reused, and in some instances, they can be acid resistant (Elias *et al.*, 2020; Jeong *et al.*, 2017; Aderibigbe *et al.*, 2023; Borges & Diaz, 2012; Zhu *et al.*, 2024). Catalyst composition, reaction temperature, loading, and the ratio of methanol to oil impact performance (Aderibigbe *et al.*, 2025; Jeong *et al.*, 2017). Difficulties persist such as reduced conversion relative to homogeneous catalysts and basic site sensitivity to water and FFA (Gadore *et al.*, 2023). Future perspectives involve improving stability, decreasing the cost of syntheses, and creating new high-efficiency and sustainability materials, including MOFs, nanostructures, and biowaste-based catalysts (Cong *et al.*, 2021; Li *et al.*, 2016; Zhang *et al.*, 2019a; Changmai *et al.*, 2023; Mukhtar *et al.*, 2022).

### Metal–Organic Frameworks (MOFs) and Covalent Organic Frameworks (COFs)

Next-generation porous materials with exceptional catalytic potential are metal–organic frameworks (MOFs) and covalent organic frameworks (COFs). MOFs, built from metal ions linked by organic molecules, are known for their exceptionally high surface area, adjustable pore structures, and tunable active sites, all of which can significantly improve both transesterification and esterification reactions (Durumin-Iya & Ismail, 2024; Gadore *et al.*, 2023). COFs, on the other hand, are composed entirely of covalently bonded organic units.

With their ordered pore structures, strong chemical stability, and potential for reuse, these materials stand out as promising options for large-scale biodiesel production (Rathod *et al.*, 2023; Garg *et al.*, 2023). Their modular design also allows researchers to fine-tune them for specific catalytic roles. Even so, the high cost of synthesis and difficulties in scaling up remain major hurdles to their broader industrial adoption.

### Biochar-Supported Nanocatalysts

Biochar-based catalysts are a great reminder that waste doesn't have to stay waste, it can be turned into something valuable. Everyday materials we usually throw away, like oak leaves, eggshells, or coffee grounds, can be converted into biochar, a substance with a large surface area, adjustable pores, and strong durability (Li & Liang, 2024; Ulukardesler, 2023). When this biochar is paired with nanometals such as Fe<sub>3</sub>O<sub>4</sub>-CuO, it becomes a catalyst that works efficiently, is cost-effective, and can even be pulled out with a magnet for reuse. A standout example comes from something as simple as oak leaves. When turned into a biochar/Fe<sub>3</sub>O<sub>4</sub>-CuO catalyst, they showed remarkable reactivity, could be separated with ease, and were durable enough to be reused again and again. Solutions like this go beyond just making biodiesel cleaner and more efficient. They give waste a second life, turning everyday leftovers into resources and creating a powerful link between renewable energy and sustainable living (Li & Liang, 2024).

### Comparative Overview of Catalyst Classes

A comparison of various catalyst types, highlighting their advantages and disadvantages, is given in Table 2. It shows how traditional, nanostructured, and emerging catalysts vary in terms of activity, reusability, adaptability to different feedstocks, and environmental impact.

**Table 2:** Comparative Overview of Catalyst Classes

Catalyst Type	Advantages	Limitations	References
Homogeneous (NaOH, KOH)	High activity, low cost	Difficult separation, wastewater, low reusability	Sulaiman <i>et al.</i> , 2025b; Bahkali <i>et al.</i> , 2024
Heterogeneous (CaO, MgO, TiO <sub>2</sub> , Zeolites)	Reusable, easy recovery, greener	Lower conversion efficiency, leaching issues	Rajak <i>et al.</i> , 2025; Ghosh <i>et al.</i> , 2024
Nanocatalysts (ZnO, Fe <sub>3</sub> O <sub>4</sub> , CNTs)	High surface area, stability, tunable properties	Costly synthesis, agglomeration	Bhan <i>et al.</i> , 2025; Joshi <i>et al.</i> , 2023
Bifunctional Catalysts	Esterification plus transesterification, efficient for high FFA feedstocks	Complex preparation, stability concerns	Rathod <i>et al.</i> , 2023; Rajak <i>et al.</i> , 2025
MOFs/COFs	Ultra-high surface area, tunable reactivity, reusability	High cost, scalability issues	Gadore <i>et al.</i> , 2023; Garg <i>et al.</i> , 2023
Biochar Composites	Waste valorization, cost-effective, magnetic recoverability	Variable quality depending on biomass	Li & Liang, 2024; Ulukardesler, 2023

### Process Intensification and Digital Integration in Biodiesel Production

A combination of process intensification and digital

technologies is reshaping the foundations of biodiesel production to increase efficiency, cost minimization, and enhance sustainability (Cheng *et al.*, 2025; Tsai &

(Tsai, 2024). Microreactors, ultrasonic-assisted, and green catalysts are examples of innovations applied in process intensification to increase reaction rates, mixing, and mass/heat transfer and reduce energy consumption and waste products, with biomass ash that contains potassium being viewed as an ecologically friendly, cost-effective catalyst (Tsai & Tsai, 2024). Adding to these physical and chemical improvements, digital integration via artificial intelligence (AI), machine learning (ML), and digital twins can provide predictive models, real-time optimization, and controlled processes, allowing operational data to be analyzed to identify optimum conditions, reaction behavior, and optimized process parameters, and digital twins can be used to simulate production at different conditions to support strong and flexible system design (Cheng *et al.*, 2025; Wang *et al.*, 2025; Hu *et al.*, 2025; Li *et al.*, 2025). Sustainability through this synergy is also ensured by minimizing energy use and waste, using green catalysts, and enabling life cycle assessment (LCA) and techno-economic analysis (TEA) to assess environmental and economic outcomes (Li *et al.*, 2025; Leuthe *et al.*, 2024; Tsai & Tsai, 2024; Khan *et al.*, 2024). Nevertheless, there are also obstacles, such as quality datasets and computing power required to have strong AI/ML models, investment in infrastructure and training to integrate digital tools (Zhang *et al.*, 2025; Ou *et al.*, 2024). To solve these issues, it is important to collaborate interdisciplinarily, and further research must introduce new and improved AI/ML algorithms, use digital twins to provide control in real-time, and implement advanced sensors and analytics to monitor and optimize processes (Zhong *et al.*, 2025; Rescanski *et al.*, 2025).

### Challenges in Industrial Implementation

Although biodiesel holds strong promise as a clean and sustainable alternative to fossil fuels, its large-scale deployment continues to face technical, economic, and environmental challenges (Yaghi *et al.*, 2025; Rocha-Meneses *et al.*, 2023). These challenges which are as diverse as catalyst stability, availability of raw material, production costs and environmental effects, must be resolved so that large scale commercialisation can be undertaken.

### Technical Challenges

Although the production of biodiesel has indeed been on the rise in recent decades, large-scale production remains constrained by its high costs, inadequate supply of raw materials, and inadequate infrastructure. Additional limitations involve catalyst deactivation, sensitivity to water and free fatty acid (FFA), and bottlenecks in mass transfer, which undermine the efficiency of the process (Anekwe and Isa, 2025; Yusuf *et al.*, 2024; Rocha-Meneses *et al.*, 2023).

### Catalyst Deactivation

Deactivation of the catalyst is one of the main obstacles to the production of efficient and sustainable biodiesel

(Anekwe & Isa, 2025). Over time, carbon deposits may clog the catalytic sites, while oxidation, heat damage and mechanical wear further reduce the catalytic efficiency (Zhou *et al.*, 2020). Problems such as migration and agglomeration, resulting in reduced surface area and reduced reactivity, also occur with nanoparticle-based catalysts (Zhao *et al.*, 2023). Regeneration methods, including oxidation, gasification and hydrogenation, may restore some activity, but it is still difficult to find affordable and sustainable solutions (Takase *et al.*, 2023).

### Water and FFA Sensitivity

The production of biodiesel is significantly influenced by impurities in feedstocks, in particular water and fatty acids. Water interferes with transesterification and the FFAs react with alkaline catalysts to form soap, reducing yields and making separation more difficult (Gadore *et al.*, 2023; Yusuf *et al.*, 2024; Abdurakhman *et al.*, 2017). Acid catalysts and heterogeneous acid resistance systems such as HNTs-Ca-Zn show promise for overcoming these problems, especially for high FFA feedstocks such as acidified palm oil (Zhu *et al.*, 2024).

### Mass Transfer Bottlenecks

In heterogeneous catalysis, mass transfer factors reduce the reaction rates, as the movement of bulk phases and the catalyst surface is limited by diffusion (Gadore *et al.*, 2023; Rocha-Meneses *et al.*, 2023). The methods of engineering, including microbubble-mediated transfer (Asif *et al.*, 2023) and the computational fluid dynamics (CFD) modeling, are useful in improving reactor designs and efficiency. Previous studies have already used CFD in fluidized bed reactors to catalytically decompose methane, which provides meaningful information that can be transferred to biodiesel reactors (Niyogi *et al.*, 2023).

### Economic Challenges

The commercialization of biodiesel is hampered because of high production costs and uncertainties in techno-economic viability (Rocha-Meneses *et al.*, 2023).

### High Synthesis Costs

Most of the expenses involved in biodiesel production are because of the feedstock and refined vegetable oils in particular are very costly (Boas *et al.*, 2022; Yaghi *et al.*, 2025). The use of alternatives like waste cooking oil (Okirie *et al.*, 2025), and by-products may help to reduce costs, and renewable and waste-derived catalysts can yield better economics and sustainability of the process (Sulaiman *et al.*, 2025a; Kosuru *et al.*, 2024; Dwivedi *et al.*, 2022).

### Techno-Economic Analysis

In order to truly evaluate the viability of biodiesel, we must enter into a comprehensive techno-economic analysis (TEA). This includes comparing the capital costs, operating expenses and the costs of the feedstock

to the costs of the final product. In doing so, TEA assists in determining the obstacles that could influence competitiveness (Abdurakhman *et al.*, 2018; Rocha-Meneses *et al.*, 2023). More recent technologies like catalytic membrane reactors (CMRs) are also expected to boost yields of difficult feeds like WCO (Abdurakhman *et al.*, 2018).

### Environmental Challenges

The argument that biodiesel is renewable does not necessarily equate to a reduced environmental footprint. The most pressing issues include feedstock cultivation, water use, greenhouse gas emissions, and the threat of eutrophication (Jan *et al.*, 2025; Motevali *et al.*, 2023).

### Feedstock Production and Land Use

This production of raw materials is the initial step in the biodiesel production process, and thus, it is a critical factor that determines the environmental footprint of the biodiesel (Garg *et al.*, 2023). Various feedstock types, such as oilseed crops, algae and waste oils, have varied environmental effects (Garg *et al.*, 2023). First generation feedstocks like soya, rapeseed and palm oil are linked to deforestation and indirect land use change, which emits hidden carbon and unsettles greenhouse gas emissions (Wang *et al.*, 2024; Garg *et al.*, 2023). When the territory covered by the production of these crops is increased, habitats are usually destroyed, and biodiversity suffers (Wang *et al.*, 2024; Zambrano-Monserrate *et al.*, 2024). Non-edible oils, waste cooking oil, and lignocellulosic biomass are examples of non-edible oils used as second generation feeds as they cause less competition to food crops and use of residues (Mata *et al.*, 2024; Garg *et al.*, 2023). However, the availability of WCO is limited and converting lignocellulosic biomass uses significant amounts of energy and is not that easy to scale (Garg *et al.*, 2023; Jeswani *et al.*, 2015). Lignocellulosic biomass is a mixture of cellulose (40-50%), hemicellulose (25-35) and lignin (15-20) (Garg *et al.*, 2023). The advantages of third generation feedstocks, especially microalgae, include a high lipid productivity into biofuel production, CO<sub>2</sub> sequestration, and the possibility to grow them on a cultivable land (Omokaro & Nafula, 2023; Tomar *et al.*, 2023; Chanda *et al.*, 2023; Parachay *et al.*, 2023). Microalgae may be especially effective in cultivating wastewater and could be used to recycle resources and treat waste water (Ilieva *et al.*, 2024; Sousa *et al.*, 2023). Nevertheless, microalgae production growth is experiencing difficulties regarding resource and energy demands, thus a drawback to its competitiveness (Chhandama *et al.*, 2023; Parakh *et al.*, 2023).

### Water Consumption and Pollution

Water is an important consideration in the production of biodiesel especially in the cultivation and processing of feedstock. The energy crop may consume water, particularly in arid and semi-arid areas (Nassar *et al.*, 2021). Moreover, agricultural activities in the use of

fertilizers and pesticides may result in water pollution by dumping into the water, thus impacting aquatic organisms and human health (Motevali *et al.*, 2023). Agriculture has always recorded greater values in most metrics of environmental impact, such as aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification, lead build-up, aquatic acidification, and aquatic eutrophication (Motevali *et al.*, 2023). Thermo-sonic assisted enzyme pre-treatment of sludge biomass has the potential to increase lipid production to biodiesel (Selvakumar *et al.*, 2019). Moreover, the process of microalgae growth on the domestic wastewater can mitigate the freshwater consumption as well as treat the wastewater, presenting a synergistic solution to the issue of resource management (Liu *et al.*, 2025).

### Greenhouse Gas Emissions

Even though it is claimed that biodiesel is a low-carbon fuel, its greenhouse gas (GHG) emissions are subject to change depending on the feedstock type, the production process and land-use change impact. Life cycle assessment (LCA) also presents a chance to evaluate the total environmental effect of biodiesel production (Nogales-Delgado, 2025; Thiruketheswaranathan, 2022; Rajaeifar *et al.*, 2018). Studies have discovered that WCO biodiesels have been able to include significantly fewer GHG emissions than petroleum diesel, whilst some energy crop biodiesels could comprise greater levels owing to land-use change (Patel & Singh, 2024; Hosseinzadeh-Bandbafha *et al.*, 2022). The production of biodiesel by transesterifying oils and fats also emits GHGs because of consuming energy and dyes (Farouk *et al.*, 2024; Ramos *et al.*, 2019). The efficiency and sustainability of transesterification can be improved by heightened catalysts such as metal oxide-based heterogeneous catalysts, and re-engineering of reaction conditions (Srikumar *et al.*, 2024; Gadore *et al.*, 2023). It can be lowered by using emerging technologies, like the conversion of algal biomass to biodiesel using ultrasonic methods, which reduce the time of reaction and energy requirements (Patle *et al.*, 2021).

### Eutrophication

Eutrophication, an over enrichment of water bodies with nutrients, is another contextual environmental issue presented by biodiesel production (Akinnowo, 2023). The nutrient runoff that can be caused by the use of fertilizers when growing feedstock contributes to algal proliferation and, as a result, to the final disappearance of oxygen in the water bodies (Motevali *et al.*, 2023). Farming activities present the best opportunity of aquatic eutrophication by the stage of bio-diesel supply chain in comparison to ginning, oil processing, transesterification, and biodiesel synthesis (Motevali *et al.*, 2023). This may ultimately result in the death of aquatic plants and animals and decline of water quality (Akinnowo, 2023). Sustainable agricultural methods like precision fertilization and combined nutrient procedures are also proven to reduce nutrient runoff and, consequently, the risks of eutrophication (Motevali *et al.*,

2023). Moreover, drawing microalgae produced through the use of wastewater streams has provided a closed-loop approach to nutrient retrieval and reuse, and reduces the release of nutrients into aquatic ecosystems (Liu *et al.*, 2025). Production of bio-diesel has presented a dual environment of opportunity as well as challenge on the development of sustainable energy. Although biodiesel is a renewable substitute to the normal fossil fuels, it has to be used carefully in regard to environmental effects. The key to this objective is the careful use of sustainable feedstocks, the maximum application of production guidelines and good management practices, which will continue to contribute to the reduction of the cumulative environmental footprint of biodiesel. Future research priorities should focus on developing cutting-edge technologies for feedstock cultivation, conversion and waste management to make biodiesel a more sustainable and more cost-efficient transport fuel. Multi-criteria decision models can help to navigate the complex list of factors involved in the production and use of biodiesel and thus to make informed and sustainable modelling decisions.

### Future Prospects

The future prospects for biodiesel production will be characterised by hybrid catalytic cracking systems, circular biorefineries (Okirie *et al.*, 2025), technical and digital innovation and the empowerment of policy frameworks. All these dimensions demonstrate the potential of biodiesel as, not only, a renewable alternative fuel but also as a key element of the sustainable circular bioeconomy.

### Hybrid Catalysts

Catalytic innovation is increasingly focused on hybrid enzyme–nanocatalyst systems that combine the precision of lipases with the strength and reusability of nanomaterials. Studies have shown that attaching lipases to nanostructured materials such as Fe<sub>3</sub>O<sub>4</sub> nanoparticles and metal–organic frameworks (MOFs) can achieve biodiesel conversion rates of more than 90%, while maintaining performance across multiple cycles (Zhu *et al.*, 2024). Through enhanced enzyme stability and streamlined catalyst recovery, these systems provide a dependable, non-toxic, and recyclable way to boost biodiesel production.

### Integration into Circular Biorefineries

Both the financial and environmental performance of integrated circular bio-refineries can be enhanced by the incorporation of biodiesel. Feedstocks such as used cooking oils, animal fats, algae residues and lignocellulosic biomass help to reduce dependence on edible oils and to minimise the competition between food and fuel (Singh *et al.*, 2021). At the same time, by-products such as glycerol can be converted into chemicals or microbial feedstocks, while solid residues can be anaerobically digested to provide renewable heat and electricity (Nawin *et al.*, 2024). This integration supports the zero waste

objectives and places biodiesel as a strategic contributor to the bioeconomy.

### Engineering and Digital Innovations

Technological progress and digital integration are reshaping the production routes for biodiesel. Digital twin technologies provide real-time process monitoring, predictive maintenance, and closed-loop optimization, improving operational efficiency and system resilience (Garg *et al.*, 2023). Meanwhile, supercritical transesterification of methanol has demonstrated fatty acid methyl ester (FAME) yields exceeding 90% in the absence of catalysts, which eases purification and minimizes chemical requirements. Nevertheless, the scale of application is limited by the energy requirements of high-pressure systems. Collectively, digitalization and supercritical processing constitute complementary approaches to more sustainable and resilient biodiesel production.

### Policy and Governance Frameworks

The issue of policy continues to be a determinant of biodiesel adoption. The Renewable Energy Directive II (RED II) by the European Union shows how a renewable energy obligation and specific funding can help catalyze the implementation of waste-based biofuels (European Commission, 2018; European Court of Auditors, 2023). In contrast, the Biofuel Policy 2007 shows that contemporary Nigeria is plagued by poor implementation and institutional disintegration, which compromises the otherwise noble objectives (Aduloju, 2021; Iseghohime, 2023). Timely policy, consistent policy and market-driven incentives will be crucial to supporting the scale up of catalytic breakthroughs and the national transition to biodiesel all around the world (Anil *et al.*, 2024).

### Outlook

In the future, the contribution of biodiesel into the low-carbon transformation will rely on the collaborative development of hybrid catalysts, integrated biorefining systems, engineering technology and sensible political implementation. Hybrid enzyme–nanocatalyst systems provide high-performance, scalable catalytic platforms; biorefineries deliver functionality by ensuring waste is valued and by being circular; digital engineering offers efficiency and resilience; and policy frameworks enable industrial implementation. All these lines of reasoning lead to a future where biodiesel can play a significantly different role in becoming not only a renewable transportation power source but as part of the larger global toolkit of circular bioeconomy efforts.

### CONCLUSION

The latest developments in catalytic formulations, process intensification solutions and systemic integration have significantly intensified the process of biodiesel synthesis, thus contributing to improved operational efficiency, product selectivity, and overall sustainability.

Some promising emerging technologies, such as artificial intelligence, microreactor systems, and hybrid enzyme-nanocatalyst assemblies, offer capability at scales of predictive optimisation and scalable pathways to production, but remain constrained by persistent issues with catalyst deactivation, feedstock cost variability, and environmental trade-offs. Combining biodiesel production into the contexts of circular biorefineries can reduce operation costs, highlight residual streams, and aid on zero-waste aims. The future development is expected to rely on the advancement of hybrid catalytic platforms, advanced engineering solutions, and facilitating policy measures to allow large-scale application in industry. Taken together, these new developments highlight the importance of biodiesel as a cornerstone of the circular bioeconomy and a key player in the global low-carbon energy transition.

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