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Review

Nanocatalysts in Transesterification: A Sustainable Catalyst Revolution for Biodiesel Production

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Abstract

The urgent need for sustainable and renewable energy sources has intensified research on biodiesel as an alternative to fossil fuels. Among various production pathways, the transesterification reaction is a widely adopted method for converting feedstock oils into fatty acid methyl esters (FAMEs). Traditional homogeneous catalysts, while effective, face critical challenges such as complex separation, limited reusability, and significant energy requirements. Nanocatalysts have emerged as a transformative solution, offering high surface area, enhanced catalytic activity, and improved reaction kinetics that significantly boost biodiesel yields. Metal oxide nanocatalysts, including calcium oxide (CaO), zinc oxide (ZnO), and cerium oxide (CeO), as well as carbon-based and zeolite nanocatalysts, have demonstrated superior performance due to their tunable properties and stability. In addition, magnetic nanocatalysts and biochar-based materials provide efficient recovery options and align with green chemistry principles. Nanocatalysts optimize critical process parameters such as catalyst loading, methanol-to-oil ratio, and reaction temperature, resulting in biodiesel yields exceeding 90% under mild conditions. Studies have highlighted their ability to lower activation energy, enhance selectivity, and reduce overall process costs by allowing multiple reuse cycles without performance degradation. However, challenges such as high fabrication costs, particle uniformity, and potential environmental impacts must be addressed for widespread adoption. Future research directions include the development of cost-effective green synthesis methods, hybrid catalytic systems integrating enzymatic and nano components, and the use of non-edible feedstocks to enhance sustainability. By combining high catalytic efficiency, reusability, and environmental benefits, nanocatalysts represent a breakthrough in biodiesel production technology. Their potential to simplify purification, reduce waste, and enable scalable, eco-friendly processes positions them as a key driver in the global shift toward renewable energy solutions.

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1. Introduction

The growing demand for renewable energy has driven biodiesel research as a sustainable alternative to fossil fuels. Among the key steps in biodiesel production is the transesterification reaction, where feedstock oils are converted into fatty acid methyl esters (FAMEs). Conventional homogeneous catalysts, although effective, face limitations such as difficult separation, high energy requirements, and wastewater generation. Nanocatalysts have emerged as a revolutionary solution, offering superior catalytic performance, easy recyclability, and improved sustainability compared to traditional catalysts (Mofijur et al., 2021; Mittal et al., 2024; Ahmed et al., 2023). Nanocatalysts possess several unique advantages that make them ideal for biodiesel production. Due to their nanoscale dimensions, nanocatalysts have an exceptionally high surface area that enhances the contact between active sites and reactants, resulting in faster reaction kinetics and improved selectivity (Mofijur et al., 2021; Mittal et al., 2024; Ahmed et al., 2023). These catalysts exhibit higher turnover frequencies and require lower activation energy, which allows transesterification to occur under milder conditions while achieving higher yields (Mittal et al., 2024; Ahmed et al., 2024, Sarmah & Borthakur., 2013; Borthakur 2025,Velmurugan et al., 2024). Nanocatalysts can be easily separated and reused for multiple cycles without significant loss of catalytic activity, which reduces costs and environmental

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impact (Ahmed et al., 2023; Saravanan et al., 2022; Rao et al., 2021). Many nanocatalysts are synthesized from biomass-derived sources, including plant residues, agricultural by-products, and animal waste, contributing to a greener production chain (Ahmed et al., 2023; Velmurugan et al., 2024).

2. Types of Nanocatalysts

Several classes of nanocatalysts have been explored for biodiesel synthesis:

- Metal Oxide Nanocatalysts: Calcium oxide (CaO), zinc oxide (ZnO), and cerium oxide (CeO) are widely used due to their high basicity, stability, and catalytic efficiency (Ahmed et al., 2023; Manikandan & Aalam, 2024; Davoodbasha et al., 2021; Nawaz Khan et al., 2025).
- Carbon-Based Nanocatalysts: Carbon nanotubes (CNTs), graphene derivatives, and activated carbon materials provide large surface areas and high porosity, improving mass transfer and catalytic activity (Mittal et al., 2024; Velmurugan et al., 2024).
- Zeolite-Based Nanocatalysts: Zeolite frameworks offer tunable acidity/basicity and well-defined pores, making them excellent candidates for transesterification (Mittal et al., 2024).

3. Enhancement of Transesterification Efficiency by Nanocatalysts

Nanocatalysts enhance the efficiency of the transesterification process for biodiesel production through multiple synergistic mechanisms that improve reaction kinetics, yield, and sustainability. One of the primary advantages of nanocatalysts is their high surface area and reactivity, which increases the interaction between the catalyst and reactants, thereby accelerating the conversion of oils into biodiesel. For instance, the use of nano alumina and cerium oxide catalysts in conjunction with KOH has been shown to significantly improve pine biodiesel yield by increasing the number of available active sites for the reaction (Manikandan & Aalam, 2024; Mofijur et al., 2021; Al-Abbasi et al., 2023; Chooi et al., 2021). Another critical factor is the improved catalytic activity of nanocatalysts compared to conventional catalysts. Owing to their nanoscale properties, they provide higher turnover rates and more efficient triglyceride conversion into fatty acid methyl esters (FAMEs), the primary components of biodiesel. For example, barium oxide (BaO) nanoparticles have demonstrated a maximum biodiesel yield of 78.38% under optimized conditions, reflecting their superior activity and efficiency (Mofijur et al., 2021; Al-Abbasi et al., 2023; Singh et al 2020., Borthakur & Sarmah2025; Namini et al., 2025). Nanocatalysts also offer enhanced stability and reusability, enabling them to maintain high catalytic performance across multiple cycles. This feature is vital for lowering operational costs and improving the overall sustainability of biodiesel production processes. A notable example is the Ca/wollastonite catalyst, which retained a high FAME yield of 97.59% even after five consecutive cycles of use, highlighting its durability and efficiency (Al-Abbasi et al., 2023; Corrales-Pérez et al., 2024; Saravanan et al., 2022; Qu et al., 2020). In addition, certain nanocatalysts possess magnetic properties, such as iron oxide nanoparticles (IONPs), which allow for straightforward magnetic separation and recovery. This not only improves process efficiency but also reduces energy and resource consumption during post-reaction purification (Corrales-Pérez et al., 2024). Nanocatalysts further enable the optimization of reaction conditions, including catalyst loading, temperature, and methanol-to-oil ratio, which are key parameters for maximizing biodiesel yields. For example, CaO nanocatalysts derived from waste cockle shells have achieved a biodiesel yield of 94.13% at 60°C with a reaction time of just 3 hours, showcasing the ability of nanocatalysts to operate effectively under mild conditions (Manikandan & Aalam, 2024; Chooi et al., 2021; Corrales-Pérez et al., 2024; Mittal et al., 2022). Furthermore, these catalysts are capable of reducing activation energy, thereby accelerating the reaction rate. The CaO nanocatalyst mentioned above achieved an enhanced reaction rate, producing a 27.3% FAME yield per hour under optimized conditions (Chooi et al., 2021). In conclusion, nanocatalysts significantly enhance the transesterification process by combining superior catalytic activity, high surface reactivity, stability, reusability, and the ability to fine-tune reaction parameters. Their role in lowering activation energy and enabling efficient recovery processes makes them a critical innovation for sustainable biodiesel production (Manikandan & Aalam, 2024; Borthakur et al., 2025, Mofijur et al., 2021; Al-Abbasi et al., 2023; Chooi et al., 2021; Corrales-Pérez et al., 2024; Qu et al., 2020).

4. Optimization of Reaction Parameters

Achieving high biodiesel yields requires fine-tuning of reaction parameters:

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- Methanol-to-Oil Ratio: Excess methanol drives the reaction toward higher conversion. For instance, optimal ratios include 20:1 for Se-doped ZnO nanorods and 6:1 for ZnO nanocatalysts (Rao et al., 2021; Nawaz Khan et al., 2025).
- Catalyst Loading: Nanocatalyst concentration influences reaction efficiency. Optimal loading typically ranges between 0.5 wt% and 10 wt%, depending on the feedstock and catalyst used (Nawaz Khan et al., 2025; Gurunathan & Ravi, 2015).
- Reaction Temperature and Time: Effective transesterification is generally achieved at 55°C–80°C and requires 1–4 hours of reaction time (Davoodbasha et al., 2021; Nawaz Khan et al., 2025; Gurunathan & Ravi, 2015). The various parametrs are shown in Table 1.

Table 1. Summary Table.

Parameter	Optimal Conditions	References
Methanol-to-Oil Ratio	6:1 to 20:1	Rao et al., 2021; Nawaz Khan et al., 2025
Catalyst Loading	0.5 wt% to 10 wt%	Nawaz Khan et al., 2025; Gurunathan & Ravi, 2015
Reaction Temperature	55°C to 80°C	Davoodbasha et al., 2021; Nawaz Khan et al., 2025; Gurunathan & Ravi, 2015
Reaction Time	60 minutes to 4 hours	Davoodbasha et al., 2021; Nawaz Khan et al., 2025; Gurunathan & Ravi, 2015
Types of Nanocatalysts	CaO, ZnO, CeO, Carbon-based, Zeolite-based	Mittal et al., 2024; Ahmed et al., 2023; Manikandan & Aalam, 2024; Davoodbasha et al., 2021; Nawaz Khan et al., 2025
Advantages	High surface area, catalytic efficiency, reusability, eco-friendly	Mofijur et al., 2021; Mittal et al., 2024; Ahmed et al., 2023; Velmurugan et al., 2024

5. Challenges and Future Prospects of Nanocatalysts in Enhancing Transesterification for Biodiesel Production

Despite their potential, nanocatalysts face certain challenges:

- High Synthesis Costs: Advanced fabrication methods, such as sol-gel or hydrothermal synthesis, remain expensive, hindering large-scale deployment (Kumar et al., 2019).
- Particle Uniformity: Maintaining consistent particle size and morphology is critical to ensure stable catalytic performance (Kumar et al., 2019).
- Industrial Scalability: There is a need for cost-effective, biodegradable, and robust nanocatalysts to bridge the gap between laboratory research and industrial-scale production (Farouk et al., 2024).

Nanocatalysts are poised to play a transformative role in the future of biodiesel production by significantly enhancing the efficiency of the transesterification process through innovative material design, advanced synthesis techniques, and sustainable applications. One of the key future prospects lies in the development of nanocatalysts with increased catalytic activity and larger surface area, such as metal oxides, carbon-based nanomaterials, and magnetic nanoparticles. Their high surface reactivity promotes greater interaction with feedstock oils, enabling faster reaction rates and higher biodiesel yields. For instance, nano alumina and cerium oxide have been shown to enhance both the reaction rate and the yield of biodiesel due to their abundant active sites and strong catalytic activity (Damian & Devarajan, 2024; Abdul Rahaman et al., 2025; Lim et al., 2022; Manikandan & Aalam, 2024, Saikia et al., 2023).

Another major advancement is the simplification of separation processes. Nanocatalysts, particularly magnetic ones, allow for easy recovery from reaction mixtures via magnetic decantation, thereby reducing downstream purification steps and operational costs (Damian & Devarajan, 2024; Namini et al., 2025). This approach is particularly beneficial for scaling up biodiesel production while maintaining economic feasibility. Enhanced biodiesel yield and quality are also expected outcomes of next-generation nanocatalysts. For example, $MgO/MgSO_4$ nanocatalysts have achieved biodiesel

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yields as high as 98.8%, while magnetic nanocatalysts derived from waste materials have demonstrated yields of up to 97.92%, all while producing biodiesel that meets international ASTM quality standards (Bora et al., 2022; Ghosh et al., 2024; Borthakur et al., 2023, Bousba et al., 2024).

However, the widespread adoption of nanocatalysts will require overcoming key challenges related to production cost and environmental safety. The high cost of nanoparticle synthesis, often involving complex methods like sol-gel or combustion synthesis, remains a barrier to large-scale commercialization. Future research must focus on cost-effective, green synthesis routes using renewable or waste-derived precursors (Damian & Devarajan, 2024; Abdul Rahaman et al., 2025). Additionally, concerns about nanoparticle toxicity and their long-term environmental impacts demand rigorous studies on safe handling, lifecycle assessment, and disposal strategies (Abdul Rahaman et al., 2025; Joy et al., 2025).

Optimization of reaction conditions will continue to be a critical research area. Advanced statistical and computational approaches, such as Response Surface Methodology (RSM) and artificial intelligence-assisted modeling, are expected to be increasingly used to fine-tune parameters like catalyst dosage, methanol-to-oil ratio, reaction time, and temperature to maximize both yield and energy efficiency (Manikandan & Aalam, 2024; Chaudhry et al., 2024). Another promising direction involves the utilization of non-edible and waste feedstocks, including used cooking oil and non-food crops. When paired with nanocatalysts, these feedstocks offer an environmentally friendly and economically viable solution, reducing competition with food sources (Damian & Devarajan, 2024; Chaudhry et al., 2024).

Innovative applications of nanocatalysts, such as magnetic nanocatalysts like $NaOH/CoFe_2O_4$, are also gaining attention for their high efficiency, ease of recovery, and reusability, making them attractive for industrial-scale biodiesel plants (Bousba et al., 2024). Similarly, biochar-based nanocatalysts, derived from agricultural and forestry residues, represent a sustainable and cost-effective approach to enhance transesterification and esterification reactions while upcycling waste biomass (Zandjou et al., 2024, Borthakur et al., 2022). Furthermore, the development of hybrid catalysts, which combine nano- and enzymatic catalysts, is anticipated to create unique catalytic microenvironments. This synergy can improve biodiesel yields, reduce reaction time, and open new avenues for integrating bioenergy systems into circular economy models (Chang et al., 2024, Borhakur & Medhi, 2023;).

In conclusion, the future of biodiesel production is likely to be shaped by advancements in nanocatalyst technology that prioritize sustainability, cost-efficiency, and environmental safety. By leveraging innovations in magnetic and biochar-based catalysts, hybrid systems, and green synthesis methods, nanocatalysts have the potential to revolutionize biodiesel production. Continued interdisciplinary research, spanning material science, chemical engineering, and environmental studies, will be crucial to fully unlock the capabilities of nanocatalysts for large-scale, sustainable energy generation (Damian & Devarajan, 2024; Abdul Rahaman et al., 2025; Joy et al., 2025).

6. Conclusion

Nanocatalysts represent a significant advancement in the field of biodiesel production, offering a sustainable alternative to traditional homogeneous and heterogeneous catalysts. Their unique nanoscale properties, including high surface area, enhanced reactivity, and tunable physicochemical characteristics, have revolutionized the transesterification process by increasing reaction rates, improving yields, and reducing the energy requirements of biodiesel synthesis. Metal oxide nanocatalysts such as CaO, ZnO, and CeO, as well as carbon-based and zeolite nanocatalysts, have demonstrated superior catalytic performance, while magnetic and biochar-based nanocatalysts offer the added advantage of efficient separation and reusability.

One of the most promising aspects of nanocatalysts is their ability to operate under milder reaction conditions while maintaining high conversion efficiencies. Optimized parameters—such as methanol-to-oil ratios, catalyst loading, reaction temperature, and time—have allowed biodiesel yields to exceed 90% with minimal environmental impact. Furthermore, the reusability of nanocatalysts significantly reduces overall process costs and waste generation, making them an attractive option for industrial-scale production.

Despite these advantages, several challenges remain, including high synthesis costs, difficulties in achieving uniform particle morphology, and concerns about nanoparticle toxicity and disposal. Addressing these issues requires further research into green synthesis techniques, cost-effective scale-up processes, and the development of biodegradable nanocatalysts. Additionally, integrating

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nanocatalyst technologies with non-edible feedstocks and hybrid systems, such as enzyme-nanocatalyst composites, can further enhance the sustainability and efficiency of biodiesel production.

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