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Application of Catalysts Used in Biodiesel Production - A Review

L. Nawin, Manash Kumar, Darshan and Chandrakant Thakur*
Department of Chemical Engineering, National Institute of Technology Raipur, Raipur, CG, India
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*cthakur.che@nitrr.ac.in

ABSTRACT

Biodiesel stands as a promising alternative to traditional fossil fuels for transportation, boasting renewability, biodegradability, and environmental friendliness. However, the efficiency of biodiesel production hinges on the catalytic processes that expedite the crucial transesterification reaction between triglycerides and alcohols. The choice of catalyst becomes a multifaceted decision, influenced by factors such as feedstock quality, specific reaction conditions, and the environmental footprint associated with the catalyst itself. This comprehensive paper deals the current state of catalysts employed in biodiesel production, offering readers a nuanced understanding of the subject. The catalyst landscape is explored through an intricate analysis of various types, encompassing homogeneous, heterogeneous, enzymatic, nano, and bio-derived catalysts. A critical component of the paper is the exploration of recent advancements in catalyst synthesis techniques. This includes an assessment of the performance of these novel catalysts, elucidating their potential contributions to enhancing the biodiesel production process. By offering insights into the future prospects of these catalysts within the context of biodiesel production, the paper contributes to the evolving discourse on sustainable energy sources. In pursuit of its overarching goal, the paper aspires to furnish readers with more than just an up-to-date overview; it aims to provide a thorough examination of the prevailing trends and challenges in the realm of catalyst utilization for biodiesel production. As the world seeks greener alternatives, this paper offers valuable insights that extend beyond the present, fostering a deeper understanding of the dynamics shaping the future of biodiesel production and sustainable transportation.

Keywords: Biodiesel; Catalysts; Transesterification; Biomass; Renewable energy.

1. INTRODUCTION

As a substitute for traditional fossil fuels, biodiesel is the subject of intense research and development due to the growing demand for sustainable energy sources. Because it is made from renewable resources like vegetable and animal fats, biodiesel is better for the environment because it produces fewer greenhouse gas emissions and requires less non-renewable energy sources. Biodiesel can lessen the adverse effects of air pollution, global warming, and climate change by reducing the emissions of carbon dioxide, particulate matter, sulfur dioxide, hydrocarbons, and volatile organic compounds from the combustion of petroleum-based products (Singh *et al*. 2016; Alamu *et al*. 2008). When compared to other alternative biofuels, biodiesel has greater storage and transportation qualities and is more suited to current engines (Dharma *et al.* 2016). However, effective and affordable processing techniques are essential to the commercial viability of biodiesel production. Catalysis is necessary for the generation of biodiesel because it accelerates the conversion of triglycerides into fatty acid methyl esters (FAMEs) or biodiesel. The process of transesterification occurs when triglycerides act with alcohol in with the help of a catalyst to produce glycerol and biodiesel. In addition to increasing reaction rates, catalysts lower the amount of energy needed for the process and increase product yield and quality (Zhang and Sun, 2023). The purpose of this study article is to provide a complete examination of the usage of catalysts in the production of biodiesel. It will explore the different kinds of catalysts that are employed, such as heterogeneous and homogeneous catalysts, and their modes of operation. Heterogeneous catalysts have extended time period than homogeneous catalysts. The influence of catalyst properties on transesterification kinetics and product characteristics such as acidity, basicity, and surface area will also be covered in this paper. The study will also discuss current developments and new directions in the creation of catalysts for the production of biodiesel. This involves utilizing alternative feedstocks and reaction conditions to improve process sustainability and efficiency, as well as investigating new catalyst materials like solid acids, enzymes, and nanostructured catalysts (Adewale *et al.* 2015). Biodiesel, obtained from sources that are renewable such as plant-based oils and fats from animals, is a flexible and environmentally friendly power source. Its applications span various sectors including transportation, power generation, heating, and agriculture. In transportation, biodiesel can be blended with conventional diesel or used as a pure fuel, reducing harmful emissions and promoting cleaner air. Moreover, biodiesel is utilized in power generation, heating systems, and agricultural machinery, offering efficient and eco-friendly solutions while reducing dependence on finite fossil fuels. With its diverse applications and environmental benefits, biodiesel plays a crucial role in the transition towards a more sustainable and greener energy future.

This research paper aims to provide insights for future research directions and industrial applications in the pursuit of a more sustainable energy future by synthesizing existing literature and incorporating recent findings. It also seeks to deepen our understanding of the role of catalysts in the production of biodiesel.

2. BIODIESEL PRODUCTION MECHANISM

The chemical process known as transesterification, which produces glycerol and fatty acid alkyl esters (biodiesel) from the reaction of triglycerides in vegetable or animal fats with an alcohol in the presence of a catalyst, is how biodiesel is produced using catalysts. The following is a representation of the general transesterification reaction (Ejikeme *et al.* 2010):

Alcohol + Triglyceride ⇌ Glycerol + Biodiesel

Different kinds of catalysts, such as homogeneous and heterogeneous catalysts, are used to catalyze this reaction. Strong bases like potassium hydroxide (KOH) or sodium hydroxide (NaOH) are commonly used as homogeneous catalysts. In this instance, the triglyceride's carbonyl carbon is attacked by the hydroxide ion (OH^-), which causes the reaction to proceed and produces glycerol and biodiesel. The overall reaction can be simplified as (Ejikeme *et al.* 2010):

Triglyceride + 3Methanol ⇌ 3Biodiesel + Glycerol

Heterogeneous catalysts, on the other hand, are solid materials that remain in a separate phase during the reaction. Examples include solid bases like calcium oxide (CaO) or potassium hydroxide supported on various materials. These catalysts facilitate the transesterification reaction by providing active sites for the reaction to occur on their surface. The use of catalysts in biodiesel production offers several advantages. They speed up the process, boost the production of biodiesel, and help separate glycerol from the end product. Additionally, catalysts can be reused, reducing overall production costs. However, the choice of catalyst depends on various factors including the type of feedstock, desired purity of biodiesel, reaction conditions, and economic considerations. The catalyst's reuse provides a substantial boost in heterogeneous catalysis. (Singh *et al.* 2016). (Singh and Sharma, 2017) extracted the catalyst from the outcome of the reaction mixture, cleaned it several times with ethanol, and then rinsed it with distilled water to remove the triglycerides and esters (organic substances). The recovered catalyst was dried overnight at 110 °C and utilized for the synthesis of biodiesel under ideal conditions. Experts continue to investigate new catalyst materials and optimize reaction conditions in order to improve the efficiency and sustainability of biodiesel synthesis.

Table 1. Types of various catalyst used in biodiesel production

Feedstock	Catalysts	References
Vegetable oils	Alkaline catalysts (NaOH, KOH)	Ehsan *et al.* (2015)
	Acid catalysts (H_2SO_4, HCl, other)	Karmakar *et al.* (2023)
	Nanostructured catalysts (metal nanoparticles)	Simhadri *et al.* (2024)
	Solid acid catalysts (zeolites)	Yusuff *et al.* (2022)
Animal fats	Alkaline catalysts (NaOH, KOH)	Alamu *et al.* (2008)
	Acid catalysts (H_2SO_4, HCl)	Aniokete *et al.* (2022)
	Enzymatic catalysts (lipases)	Adewale *et al.* (2015)
	Solid base catalysts (alkaline earth metal oxides)	Alptekin *et al.* (2011)
Waste cooking oil	Alkaline catalysts (NaOH, KOH)	Awogbemi *et al.* (2021)
	Acid catalysts (H_2SO_4, HCl)	Yaakob *et al.* (2013)
	Nanostructured catalysts (metal nanoparticles)	Moazeni *et al.* (2019)
	Solid base catalysts (alkaline earth metal oxides)	Gupta *et al.* (2018)
Algae	Alkaline catalysts (NaOH, KOH)	Atadashi *et al.* (2013)
	Acid catalysts (H_2SO_4, HCl)	Ghedini *et al.* (2021)
	Enzymatic catalysts (lipases)	Ferreira *et al.* (2022)
	Nanostructured catalysts (metal nanoparticles)	Li *et al.* (2021)
	Solid acid catalysts (zeolites)	Nuhma *et al.* (2021)

Table 1 clearly shows that, the above-mentioned catalysts are used in the production of biodiesel. The selection of each type is contingent upon various factors, including feedstock composition, reaction conditions, and the intended product quality. Each type carries pros and cons of its own.

2.1 Homogeneous Catalysts

Homogeneous catalysts, such as sodium or potassium hydroxide, are effective in accelerating up the transesterification reaction and are often employed in biodiesel synthesis. By interacting with alcohol to form alkoxide ions, which then react with the triglycerides in the feedstock, they help convert vegetable or animal fats into biodiesel. These catalysts are easily dissolved in alcohol to create homogenous reaction mixtures, and they are usually used in small concentrations. To reduce the negative effects on the environment, their corrosive nature necessitates cautious handling and appropriate disposal techniques. Homogeneous catalysts are still a popular option for producing biodiesel despite these difficulties because of their low cost and reliable performance.

Sodium Hydroxide (NaOH): It is widely utilized catalyst in the production of biodiesel. It is reasonably priced and efficient. The drawback is that it is extremely caustic and needs to be handled carefully (Ejikeme *et al.* 2010).

Potassium Hydroxide (KOH): KOH is frequently utilized as a catalyst in transesterification reactions, much like NaOH (Vicente *et al.* 2004). It frequently results in faster reaction rates and is more soluble in alcohol than NaOH. Because of its corrosive nature, it must be handled carefully, just like NaOH. Sodium hydroxide and potassium hydroxide are alcohol-based solutions that are occasionally utilized as catalysts in the biodiesel manufacturing process. The advantage they have over solid NaOH or KOH is that they are simpler to work with.

2.2 Heterogeneous Catalysts

Heterogeneous catalysts have various benefits over homogeneous catalysts, including the removal of the washing process (and accompanying polluted waste water) to separate the products, easier regeneration, less corrosive, safer, cheaper, and more environmentally friendly (Agarwal *et al.* 2012). At present, numerous heterogeneous base catalysts are used for the transesterification of edible oils such as soybeans, sunflower seeds, and palm da Costa Evangelista *et al.* (2016) and Dossin *et al.* (2006) developed the very first heterogeneous catalyst of its kind for biodiesel synthesis on a pilot plant with an annual output capacity of one million metric tons, utilizing Magnesium oxide (MgO) as a catalyst, triolin, and methanol as raw material. (Gadore *et al.* 2023) used heterogeneous catalysts for transesterification processes, which are supported by high acid site levels, strong catalytic durability against leakage and toxicity impacts, and the capacity to alter hydrophobic properties.

CaO (calcium oxide) or $Ca(OH)_2$ (calcium hydroxide): In the process of making biodiesel, solid base catalysts based on calcium are employed (Gungormus *et al.* 2023). Compared to homogeneous catalysts, they have the benefit of being simpler to handle and separate from the product. Additionally, they typically have less corrosiveness. Longer reaction times and higher reaction temperature might be necessary (Lani *et al.* 2023).

Sodium Silicate: In the process of making biodiesel, sodium silicate is occasionally employed as a solid catalyst (Manurung *et al.* 2024). Usually, a solid substrate such as activated carbon or silica gel provides support for it. One benefit of sodium silicate catalysts is their reusability and ease of separation from the reaction mixture.

Enzymatic Catalysts: When producing biodiesel, transesterification reactions can be catalyzed by enzymes such as lipases. Their versatility in handling different feedstocks, mild reaction conditions, and high specificity are just a few of their many benefits. Enzymatic catalysts, however, can be costly and may need particular circumstances in order to remain active. Lipase is one of the most using enzymatic catalyst in biodiesel production (Guo *et al.* 2024).

Acid Catalysts: Acid catalysts, such as sulfuric acid (H_2SO_4) or hydrochloric acid (HCl), are occasionally employed in the production of biodiesel, especially when esterifying free fatty acids found in feedstocks of low quality (Avhad *et al.* 2018). However, due to challenges in separating the catalyst from the product and potential corrosion issues, their usage is less common than that of base catalysts.

Ionic Liquids: Ionic liquids based on choline chloride have gained attention as possible biodiesel production catalysts because of their special qualities, which include high thermal stability, low volatility, and tunability (Huang *et al.* 2024). Ionic liquids based on choline chloride have demonstrated potential as transesterification reaction catalysts (Zhang & Sun, 2023).

A variety of factors affect the biodiesel production such as catalyst selection, feedstock composition, desired reaction conditions, financial concerns, and the catalyst's environmental effect (Kosuru *et al*. 2024). Each type of catalyst has pros and cons of its own. In order to increase the effectiveness and sustainability of biodiesel production, researchers are still looking into new catalysts and refining those that already exist.

2.3 Application and Future Scope

Biodiesel, a renewable and ecologically beneficial replacement for conventional diesel fuel, has recently gained popularity due to its potential to reduce reliance on fossil fuels and Greenhouse gases (GHG) emissions. Biodiesel, which is produced from biological sources like algae, animal fats, and vegetable oils, has a wide range of uses and shows promise for a sustainable future.

2.3.1 Applications of Biodiesel

Transportation Sector: The transportation sector is one of the main uses for biodiesel. Without requiring major modifications, it can be cast-off in existing diesel machines as a merger with petroleum diesel (Gupta and Agarwal, 2021). Diesel-powered trucks, buses, and other vehicles frequently use blends of biodiesel, such as B20 (20% biodiesel and 80% diesel), B5 (5% biodiesel and

95% diesel), and others. Countries without crude oil have reduced their reliance on oil imports by expanding their own domestic manufacturing and distribution of biodiesel (Rahman *et al.* 2021).

Power Generation: Diesel generators can also run on biodiesel to generate electricity (Khoobbakht *et al.* 2019). This application is especially helpful in remote locations or other places with limited access to conventional electricity sources. Generators that run on biodiesel provide a distributed and environmentally friendly option for producing power off the grid (Pirouzfar *et al.* 2022).

Agriculture and Construction Equipment: Biodiesel can power a variety of agricultural and construction equipment, including tractors, harvesters, and bulldozers (Zheng *et al.* 2022). Using biodiesel in these machines, farmers and construction corporations can decrease their carbon footprint and promote sustainable practices in their operations.

Marine Transportation: Biodiesel has demonstrated potential as a fuel for ships and boats operating in the maritime industry. Marine engines in some areas use blends of biodiesel and gasoline to cut emissions and adhere to environmental laws governing maritime transportation (Agarwal, 2007).

Heating Oil: In both residential and commercial heating systems, biodiesel (Huang *et al.* 2024). Compared to conventional heating oil, biodiesel burns cleaner and releases fewer pollutants like sulfur oxides and particulate matter into the air.

2.3.2 Future Scope of Biodiesel:

Environmental Sustainability: As air pollution and climate change become more pressing issues, there will likely be a rise in demand for fuels that are environmentally friendly, such as biodiesel (Marwaha and Subramanian, 2024). The production of biodiesel emits fewer greenhouse gases than that of petroleum diesel, which makes it a desirable alternative for lowering the carbon footprint of a variety of industries.

Energy Security: By lowering reliance on imported fossil fuels, biodiesel presents a viable way to improve energy security (Du *et al.* 2018). Because biodiesel can be made domestically from renewable feedstocks, it can help reduce the risks associated with geopolitical unrest and oil price fluctuations while also promoting energy independence.

Technological Advancements: Current research and development efforts are concentrated on enhancing the biodiesel's performance characteristics and efficiency of production (Benti *et al.* 2023). Future developments in biofuel technology, such as the creation of new feedstocks, enhanced engine compatibility, and optimized production procedures, are anticipated to boost biodiesel's viability and competitiveness (Günay *et al.* 2019).

Policy Support: Government initiatives to promote renewable fuels and lower carbon emissions are anticipated to be the main drivers of the biodiesel market's expansion (Li *et al.* 2023). The use of biodiesel is encouraged by incentives like tax credits, subsidies, and renewable fuel requirements, which also improve the market conditions for producers and consumers.

Emerging Markets: Biodiesel presents opportunities for expansion into emerging markets, particularly in regions with abundant biomass resources and growing energy demand (Li *et al.* 2023). The cost of biodiesel production is very much relies on feedstock price (Marchetti, 2011).Developing countries with agricultural economies can leverage biodiesel production as a means of rural development, job creation, and economic growth while addressing energy access and environmental challenges.

3. CONCLUSION

One essential component of the development of sustainable energy is the use of catalysts in the biodiesel production process. Triglycerides in plant-based and animal-based fats are transformed into glycerol and biodiesel via the transesterification process, which is facilitated by catalysts. Both homogeneous and heterogeneous catalysts are significant in this method because they offer advantages such as faster reaction rates, greater yields, and easier byproduct separation. Homogeneous catalysts, such as potassium and sodium hydroxides, are frequently employed because of their affordability and efficiency. To get rid of them from the finished product, though, careful handling and neutralization procedures are needed. Conversely, heterogeneous catalysts, like potassium hydroxide and calcium oxide supported on different materials, have benefits like reusability and ease of separation, which help with cost-effectiveness and environmental sustainability. The composition of the feedstock, the desired level of product purity, the reaction conditions, and economic considerations all play a role in the catalyst selection process. The development of new catalyst materials, reaction condition optimization, and alternative feedstock exploration are the main areas of ongoing research aimed at improving the sustainability and efficiency of biodiesel production. All things considered, the use of catalysts in the production of biodiesel is a promising path toward the development of renewable energy, providing a competitive substitute for fossil fuels while reducing environmental effects. The biodiesel industry will grow and remain viable with continued advancements in catalyst technology and process optimization, which will ultimately lead to a more sustainable energy future.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Adewale, P., Dumont, M. J., and Ngadi, M., Enzyme-catalyzed synthesis and kinetics of ultrasonic-assisted biodiesel production from waste tallow, *Ultrason Sonochem*, 27, 1–9 (2015). https://doi.org/10.1016/j.ultsonch.2015.04.032

Agarwal, A. K., Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines, *Prog. Energy Combust. Sci.*, 33 (3), 233–271 (2007). https://doi.org/10.1016/j.pecs.2006.08.003

Agarwal, M., Chauhan, G., Chaurasia, S.P., and Singh, K., Study of catalytic behavior of KOH as homogeneous and heterogeneous catalyst for biodiesel production, *J Taiwan Inst Chem Eng*, 43 (1), 89–94 (2012). https://doi.org/10.1016/j.jtice.2011.06.003

Alamu, O.J., Waheed, M.A., and Jekayinfa, S.O., Effect of ethanol–palm kernel oil ratio on alkali-catalyzed biodiesel yield, *Fuel*, 87 (8–9), 1529–1533 (2008). https://doi.org/10.1016/j.fuel.2007.08.011

Alptekin, E., and Canakci, M., Optimization of transesterification for methyl ester production from chicken fat, *Fuel*, 90 (8), 2630–2638 (2011). https://doi.org/10.1016/j.fuel.2011.03.042

Aniokete, T.C., Sadare, O.O., and Daramola, M.O., Prospects of biodiesel production from waste animal fats,. In: *Waste and Biodiesel. Elsevier*, 17–44 (2022). https://doi.org/10.1016/B978-0-12-823958-2.00002-1

Atadashi, I.M., Aroua, M.K., Abdul Aziz, A.R., and Sulaiman, N.M.N., The effects of catalysts in biodiesel production: A review, *Journal of Industrial and Engineering Chemistry*, 19 (1), 14–26 (2013). https://doi.org/10.1016/j.jiec.2012.07.009

Avhad, M. R., Gangurde, L. S., Sánchez, M., Bouaid, A., Aracil, J., Martínez, M., and Marchetti, J.M., Enhancing Biodiesel Production Using Green Glycerol-Enriched Calcium Oxide Catalyst: An Optimization Study, *Catal Letters*, 148 (4), 1169–1180 (2018). https://doi.org/10.1007/s10562-018-2312-9

Awogbemi, O., Kallon, D.V. Von., Aigbodion, V.S., and Panda, S., Advances in biotechnological applications of waste cooking oil, *Case Studies in Chemical and Environmental Engineering*, 4 100158 (2021). https://doi.org/10.1016/j.cscee.2021.100158

Benti, N.E., Aneseyee, A.B., Geffe, C.A., Woldegiyorgis, T.A., Gurmesa, G.S., Bibiso, M., Asfaw, A.A., Milki, A.W., and Mekonnen, Y.S., Biodiesel production in Ethiopia: Current status and future prospects, *Sci Afr*, 19 e01531 (2023). https://doi.org/10.1016/j.sciaf.2022.e01531

da Costa Evangelista, J.P., Gondim, A.D., Souza, L. Di., and Araujo, A.S., Alumina-supported potassium compounds as heterogeneous catalysts for biodiesel production: A review, *Renewable and Sustainable Energy Reviews*, 59 887–894 (2016). https://doi.org/10.1016/j.rser.2016.01.061

Dharma, S., Ong, H.C., Masjuki, H.H., Sebayang, A.H., and Silitonga, A.S., An overview of engine durability and compatibility using biodiesel–bioethanol–diesel blends in compression-ignition engines, *Energy Convers Manag*, 128 66–81 (2016). https://doi.org/10.1016/j.enconman.2016.08.072

Dossin, T.F., Reyniers, M.-F., Berger, R.J., and Marin, G.B., Simulation of heterogeneously MgO-catalyzed transesterification for fine-chemical and biodiesel industrial production, *Appl Catal B*, 67 (1–2), 136–148 (2006). https://doi.org/10.1016/j.apcatb.2006.04.008

Du, E., Cai, L., Huang, K., Tang, H., Xu, X., and Tao, R., Reducing viscosity to promote biodiesel for energy security and improve combustion efficiency, *Fuel*, 211 194–196 (2018). https://doi.org/10.1016/j.fuel.2017.09.055

Ehsan, M., and Chowdhury, M.T.H., Production of Biodiesel Using Alkaline Based Catalysts From Waste Cooking Oil: A Case Study, *Procedia Eng*, 105 638–645 (2015). https://doi.org/10.1016/j.proeng.2015.05.042

Ejikeme, P. M., Anyaogu, I. D., Ejikeme, C. L., Nwafor, N. P., Egbuonu, C. A. C., Ukogu, K., Ibemesi, J. A., Catalysis in Biodiesel Production by Transesterification Processes-An Insight. E-J. *Chem*, 7, 689051 (2010). https://doi.org/10.1155/2010/689051

Ferreira Mota, G., Germano de Sousa, I., Luiz Barros de Oliveira, A., Luthierre Gama Cavalcante, A., da Silva Moreira, K., Thálysson Tavares Cavalcante, F., Erick da Silva Souza, J., Rafael de Aguiar Falcão, Í., Guimarães Rocha, T., Bussons Rodrigues Valério, R., Cristina Freitas de Carvalho, S., Simão Neto, F., de França Serpa, J., Karolinny Chaves de Lima, R., Cristiane Martins de Souza, M., and dos Santos, J.C.S., Biodiesel production from microalgae using lipase-based catalysts: Current challenges and prospects, *Algal Res*, 62 102616 (2022). https://doi.org/10.1016/j.algal.2021.102616

Gadore, V., Mishra, S. R., Yadav, N., Yadav, G. and Ahmaruzzaman, Md., Metal oxide-based heterogeneous catalysts for biodiesel production, *Next Sustainability*, 2, 100012 (2023). https://doi.org/10.1016/j.nxsust.2023.100012

Ghedini, E., Taghavi, S., Menegazzo, F., and Signoretto, M., A Review on the Efficient Catalysts for Algae Transesterification to Biodiesel, *Sustainability*, 13 (18), 10479 (2021). https://doi.org/10.3390/su131810479

Günay, M.E., Türker, L., and Tapan, N.A., Significant parameters and technological advancements in biodiesel production systems, *Fuel*, 250 27–41 (2019). https://doi.org/10.1016/j.fuel.2019.03.147

Gungormus, E., Seker, E., and Alsoy Altinkaya, S., Antifouling Polydopamine-Modified Poly (ether sulfone) Membrane Immobilized With Alumina-Calcium Oxide Catalyst For Continuous Biodiesel Production, *Fuel*, 349 128685 (2023). https://doi.org/10.1016/j.fuel.2023.128685

Guo, J., Wang, Y., and Fang, Z., Covalent immobilization of lipase on magnetic biochar for one-pot production of biodiesel from high acid value oil, *Bioresour Technol*, 394 130237 (2024). https://doi.org/10.1016/j.biortech.2023.130237

Gupta, J.G., and Agarwal, A.K., Engine durability and lubricating oil tribology study of a biodiesel fuelled common rail direct injection medium-duty transportation diesel engine, *Wear*, 486–487 204104 (2021). https://doi.org/10.1016/j.wear.2021.204104

Gupta, A.R., and Rathod, V.K., Waste cooking oil and waste chicken eggshells derived solid base catalyst for the biodiesel production: Optimization and kinetics, *Waste Management*, 79 169–178 (2018). https://doi.org/10.1016/j.wasman.2018.07.022

Huang, Z., ChenYang, Y., Wang, X., Cai, R., and Han, B., Biodiesel synthesis through soybean oil transesterification using choline-based amino acid ionic liquids as catalysts, *Ind Crops Prod*, 208 117869 (2024). https://doi.org/10.1016/j.indcrop.2023.117869

Karmakar, B., Datta, A., Mishra, J.R., Rokhum, S.L., and Halder, G., Catalysed biodiesel synthesis from non-edible Nagkesar and Rubber seed oil blends using C1-C3 alcohol mixtures: Process optimization, kinetics and thermodynamics, *Bioresour Technol Rep*, 24 101618 (2023). https://doi.org/10.1016/j.biteb.2023.101618

Khoobbakht, G., Karimi, M., and Kheiralipour, K., Effects of biodiesel-ethanol-diesel blends on the performance indicators of a diesel engine: A study by response surface modeling, *Appl Therm Eng*, 148 1385–1394 (2019). https://doi.org/10.1016/j.applthermaleng.2018.08.025

Kosuru S. M. Y., Delhiwala Y., Koorla P. B., and Mekala M., A review on the biodiesel production: Selection of catalyst, Pre-treatment, Post treatment methods, *Green Technol and Sustain,* 2(1), 100061, (2024). https://doi.org/10.1016/j.grets.2023.100061

Lani, N.S., Ngadi, N., Mohammed Inuwa, I., Anako Opotu, L., Zakaria, Z.Y., and Haron, S., A cleaner approach with magnetically assisted reactor setup over CaO-zeolite/Fe3O4 catalyst in biodiesel production: Evaluation of catalytic performance, reusability and life cycle assessment studies, *J Clean Prod*, 419 138329 (2023). https://doi.org/10.1016/j.jclepro.2023.138329

Li, F., Hülsey, M.J., Yan, N., Dai, Y., and Wang, C.-H., Co-transesterification of waste cooking oil, algal oil and dimethyl carbonate over sustainable nanoparticle catalysts, *Chemical Engineering Journal*, 405 127036 (2021). https://doi.org/10.1016/j.cej.2020.127036

Li, Y., Wen, Y., Chen, B., Fu, X., and Wu, Y., The dilemma and potential development of biodiesel in China - In view of production capacity and policy, *Energy for Sustainable Development*, 75 60–71 (2023). https://doi.org/10.1016/j.esd.2023.05.005

Manurung, R., Hasibuan, R., and Siregar, A.G.A., Preparation and characterization of lithium, sodium, and potassium silicate from palm leaf as a potential solid base catalyst in developed biodiesel production, *Case Studies in Chemical and Environmental Engineering*, 9 100543 (2024). https://doi.org/10.1016/j.cscee.2023.100543

Marchetti, J.M., The effect of economic variables over a biodiesel production plant, *Energy Convers Manag*, 52 (10), 3227–3233 (2011). https://doi.org/10.1016/j.enconman.2011.05.008

Marwaha, A., and Subramanian, K.A., Performance enhancement and emissions reduction of ethanol-fueled spark ignition engine with hydrogen, Biofuels, *Bioproducts and Biorefining*, 18 (3), 701–719 (2024). https://doi.org/10.1002/bbb.2539

Moazeni, F., Chen, Y.-C., and Zhang, G., Enzymatic transesterification for biodiesel production from used cooking oil, a review, J Clean Prod, 216 117–128 (2019). https://doi.org/10.1016/j.jclepro.2019.01.181

Nuhma, M.J., Alias, H., Tahir, M., and Jazie, A.A., Microalgae biomass conversion into biofuel using modified HZSM-5 zeolite catalyst: A review, Mater Today Proc, 42 2308–2313 (2021). https://doi.org/10.1016/j.matpr.2020.12.320

Pirouzfar, V., Sakhaeinia, H., and Su, C.-H., Power generation using produced biodiesel from palm oil with GTG, STG and combined cycles; process simulation with economic consideration, *Fuel*, 314 123084 (2022).
https://doi.org/10.1016/j.fuel.2021.123084

Rahman, A., Dargusch, P., and Wadley, D., The political economy of oil supply in Indonesia and the implications for renewable energy development, *Renewable and Sustainable Energy Reviews*, 144 111027 (2021).
https://doi.org/10.1016/j.rser.2021.111027

Simhadri, K., Rao, P.S., and Paswan, M., Improving the combustion and emission performance of a diesel engine with TiO_2 nanoparticle blended Mahua biodiesel at different injection pressures, *International Journal of Thermofluids*, 21 100563 (2024).
https://doi.org/10.1016/j.ijft.2024.100563

Singh, V., Hameed, B.H., and Sharma, Y.C., Economically viable production of biodiesel from a rural feedstock from eastern India, P. pinnata oil using a recyclable laboratory synthesized heterogeneous catalyst, *Energy Convers Manag*, 122 52–62 (2016).
https://doi.org/10.1016/j.enconman.2016.05.030

Singh, V., and Sharma, Y.C., Low cost guinea fowl bone derived recyclable heterogeneous catalyst for microwave assisted transesterification of Annona squamosa L. Seed oil, *Energy Convers Manag*, 138 627–637 (2017).
https://doi.org/10.1016/j.enconman.2017.02.037

Vicente, G., Martínez, M., and Aracil, J., Integrated biodiesel production: a comparison of different homogeneous catalysts systems, *Bioresour Technol*, 92 (3), 297–305 (2004).
https://doi.org/10.1016/j.biortech.2003.08.014

Yaakob, Z., Mohammad, M., Alherbawi, M., Alam, Z., and Sopian, K., Overview of the production of biodiesel from Waste cooking oil, *Renewable and Sustainable Energy Reviews*, 18 184–193 (2013).
https://doi.org/10.1016/j.rser.2012.10.016

Yusuff, A.S., Gbadamosi, A.O., and Atray, N., Development of a zeolite supported CaO derived from chicken eggshell as active base catalyst for used cooking oil biodiesel production, *Renew Energy*, 197 1151–1162 (2022).
https://doi.org/10.1016/j.renene.2022.08.032

Zhang, Y., and Sun, S., A review on biodiesel production using basic ionic liquids as catalysts, *Ind Crops Prod*, 202 117099 (2023).
https://doi.org/10.1016/j.indcrop.2023.117099

Zheng, B., Chen, J.-Y., Song, Z., Mao, E., Zhou, Q., Luo, Z., and Liu, K., Prediction and optimization of emission in an agricultural harvest engine with biodiesel-diesel blends by a method of ANN and CMA-ES, *Comput Electron Agric*, 197 106903 (2022).
https://doi.org/10.1016/j.compag.2022.106903