

# Nanoarchitecture of Solid Base Catalysts for the Accelerated Production of Biodiesel

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## ABSTRACT

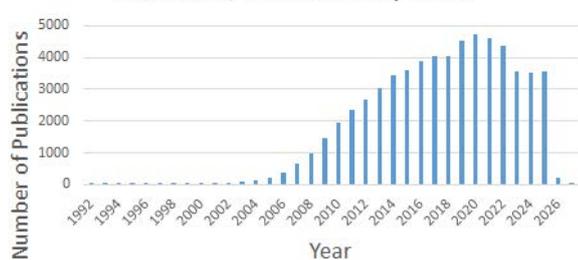
Biodiesel is an ideal substitute to fossil based fuels, namely, gasoline (32 MJ/L) and diesel (42-45 MJ/kg), owing to the closeness of the energy density values. Automobile industry and chemicals and petrochemicals industries are the key market for the product. Moreover, the feedstock used for the production of the fuel biodiesel is sustainable (lipids from freshwater micro algae and marine macro algae and waste cooking oil which is a zero value waste and many others). This makes the biodiesel product a commercial success and highly competitive in the market. Biodiesel has a huge market in the transportation sector. The fuel biodiesel will be used in the day-to-day life of common man, in the transportation sector. In layman terms the market potential of biodiesel is as great as the market potential of gasoline and diesel, the workhorses of the transportation industry. With rapidly changing geopolitical and trade relationships across the globe there is now a greater need for self-reliance in Energy for any of the developing nations. Recently, with nearly 50 % tariff from the US government on the Indian exports due to the oil imports from the Russia there is greater need for the development of processes for home-made generation of transportation fuels like biodiesel that would reduce the dependence on the crude oil imports. This is not only relevant to India but also for other developing nations in Asia and Africa, which are often called as the third-world nations.

**Keywords:** Automobile Industry; Biodiesel; Petrochemicals; UN Sustainable Development Goals; Well-Being; Good Health; Climate Action

## INTRODUCTION

Ever since the disclosure of the first patent on biodiesel production by Koracs from Hungary in the year 1993 with biodiesel as an alternative to fossil based engine oil [1], a phenomenal growth in the R & D activity of biodiesel production is witnessed with over 62, 371 publications in the web of Science database with the search keyword, namely, "biodiesel" as on 7<sup>th</sup> February 2026 as shown in Figure 1.

Web of Science: Search keywords:  
Biodiesel, 7th February 2026



**Figure 1:** The phenomenal growth of the R and D activity in the field of biodiesel production as a petroleum alternative.

## Recent Advances in Catalytic Methods for the Accelerated Biodiesel Production

In particular, rapid progress has been made in the development of feedstock, catalysts, and technology for the large scale, demand based, and economically competitive production of biodiesel during the period, 2021-2027 as depicted in Table 1.

Feedstock	Reference	Catalyst	Reference	Technology	Reference
<i>Citrullus vulgaris</i>	2	MOFs and COFs	11	Machine learning technology	20
<i>Xanthium strumarium and Mesua assamica</i>	3	Halloysite supported ZnO/SnO <sub>2</sub> heterojunction photocatalyst	12	Microwave; Ultrasound; Supercritical transesterification; genetic engineering; Plasma discharge; microchannel reactor; machine learning	21
Handal	4	ZIF-8 MOF-derived nanocatalyst	13	Micro reactor; membrane reactor; microwave; reactive distillation; centrifugal contractor	22
Pennycress Oil	5	Acid-base bifunctional ZnF <sub>2</sub>	14	Machine learning-response surface optimization approach	23
<i>Dunaliella salina</i> microalgae	6	TiO <sub>2</sub> nanoparticles	15	Life cycle assessment and techno-economic analysis	24
Waste Cooking Olive Oil and Sunflower Oil	7	SAPO-34 decorated with Mo and W oxides	16	Ultrasonic treatment	25
Jatropha	8	NaOH/ CoFe <sub>2</sub> O <sub>4</sub> magnetic nano-catalyst	17	Artificial intelligence and machine learning	26
<i>Pongamia pinnata</i>	9	H <sub>6</sub> PV <sub>3</sub> MoW <sub>8</sub> O <sub>40</sub> supported on magnetic Fe <sub>3</sub> O <sub>4</sub> /ZIF-8 composites	18	Integrated 3D printed microreactors and microseparators	27
Fish waste	10	Ni/Si/ MgO photocatalyst	19	Enzymes with ionic liquid and ultrasound based process intensification	28

**Table 1:** Advances in the development of feedstock, catalysts and technology for the production of biodiesel [2-28].

However, the synergetic use of microwave irradiation with the solid base catalyst, namely, SrO with waste cooking oil as feedstock stands out [29-33].

#### Latest technology for rapid production of biodiesel at industrial scale

To augment the rapidly increasing need for the commercially viable process for biodiesel production, a special issue has been

launched with the title “Accelerated production of biodiesel” on 10<sup>th</sup> January 2022 in the journal bioengineering. Within a short span of 20 months, enormous interest is aroused around the research groups working on this topic and 10 research groups from 9 nations have contributed 11 landmark papers to this special issue. The highlights of the 6 research articles and 5 review papers published as a reprint of the special issue were summarized in Table 2.

S No	Highlights	Reference
1	Waste alkaline solution (WAS, pH = 13.3) is a by-product of the industrial Al production by Bayer's process. The composition of the WAS (metal oxides, hydroxides, and silicates) is suitable for catalyzing the transesterification of waste cooking oil (WCO) and methanol to produce fatty acid methyl ester (FAME, biodiesel). The yield of biodiesel was > 99 % under modest reaction conditions (T = 60 °C; $\tau$ = 30 min; WAS amount = 0.204 molL <sup>-1</sup> ; WAS/WCO = 0.019 % (w/w); The process has positive environmental and economic implications at an industrial scale.	34
2	The key to solving problems in any realm of human activity is to use the challenges as opportunities. It is more so in the chemical industry, namely, the upcoming biorefinery. Roncaglia et al., precisely addressed the challenges of the inevitable glycerol by-product formation in the biodiesel producing transesterification process and also the inevitable CO <sub>2</sub> emission upon the combustion of the biodiesel. The smart strategy to solve the challenge was to convert the glycerol into the glycerol carbonate. A continuous flow process for the reaction of equimolar mixtures of CO <sub>2</sub> (ensured by the modest molar excess of urea) and glycerol to form glycerol carbonate is developed. Thus urea is effectively used as the CO <sub>2</sub> precursor altering the thermodynamic process parameters favourably. Issue of the high viscosity of the reaction medium was overcome successfully by dilution of the reaction constituents with water and also by maintaining a suitable low pressure (< 400 mm Hg). The yield of glycerol carbonate (GC) is ~ 42 %. The pressure constraint was the limiting factor pertaining to the product yield. For the first time multiple pass tubular reactor technology was used for such a process	35
3	Fahad Rehman et al., developed the microbubble interfacial technology (as a substitute to the stirred tank reactors) for the production of biodiesel using micro algae (Spirulina) as the feedstock. Microbubble mediated mass transfer technology is being exploited at an industrial scale. However, the current studies only dealt with the lab-scale experiments with a 100 mL batch. Para-toluene sulphonic acid (PTSA) is used a catalyst. A micro algal oil (MO) conversion into biodiesel as high as > 99 % is obtained under modest reaction	36

	conditions (MO:Methanol = 1:23.73; $\tau$ = 60 min; $T$ = $70 \pm 5$ °C; $P$ = 1 bar; Catalyst: PTSA, 3.3 wt.% of MO; Pseudo first order reaction; Activation energy, $E_a$ = $10.01 \pm 0.3$ kJ/mol).	
4	Anita Salic and coworkers developed deep eutectic solvents (DES) for the purification (extraction of the by-product glycerol) biodiesel in a micro-extractor. Among the 12 DESs tested the choline chloride, ChCl:Ethylene glycol, EG (1:3) showed high extraction efficiency and the least viscosity. Optical extraction process parameters include, $T$ = 40 °C, residence time, $\tau$ = 0.50 min; biodiesel:DES = 1:9 (v/v), glycerol removed = $52.99 \pm 5.23$ %. Use of different micro channel diameters and different residence times did not contribute to the process enhancement, while the integrated system with two microextractors in series was effective for glycerol removal. Using this method complete purification of biodiesel is achieved in 1 minute.	37
5	Micro algal biomass (Desmodesmus sp. EJ8-10) when cultured in anaerobic digestion waste water improved the lipid content in the micro algae by 21.8 %. The lipid content is the fraction that is transesterified to FAME (biodiesel) upon reaction with methanol in the presence of the base catalyst. Greater lipid content means great biodiesel amount. Moreover, the environmental impact too was lower (388.9 mPET2000) in the case of micro algal biomass cultured in anaerobic digestate wastewater.	38
6	Fahad Rehman and coworkers exploited the microbubble mediated mass transfer technology for intensifying the transesterification of the waste cooking oil (WCO) as well as the esterification of the free fatty acids in the oil (present as a contaminant) for the production of biodiesel using a bimetallic base catalyst (7 % Sr/ZrO <sub>2</sub> ) and an acid catalyst respectively. Conversion as high as 85 % was achieved in 20 minutes. The reaction was found to follow a pseudo-first order kinetics with an activation energy value of 7 kJ/mol. The catalyst was reused for 7 reaction runs. The interface of the microbubbles was found to play a complex role in the conversion of the WCO into the biodiesel. The microbubble interfaces act as a host for the bimetallic catalyst particles. The single step esterification (acid catalyzed) and the transesterification (base catalyzed) was found to be less energy consuming and more energy-efficient.	39

7	<p>Dhurba Neupane provided a review on the cultivation of bioenergy feedstock for the production of biofuels for reducing the reliance on fossil based resources and also for solving the problems like food vs fuel conflict, global warming, and the catastrophic consequences of climate change. Insights were provided on the possibilities of various biofuels from biomass, methods of production, key factors affecting the biodiesel production, nature of the catalysts, and the emission of possible greenhouse gases upon combusting the biodiesel. Emphasis was laid on the methods for the development of the third (algal biomass) and the fourth (genetically modified algal biomass with increased lipid/carbonhydrate content) generation feedstock.</p>	40
8	<p>The review article of Qiuyun Zhang, Jialu Wang, Yutao Zhang and co-workers, by coincidence, deals with the use of Zr based metal organic frame works (MOFs) as catalysts for the transesterification reaction for the production of biodiesel. The discovery and the development of the MOF based materials is a Nobel winning contribution to the field of Chemistry by Susumu Kitagawa (Kyoto University, Japan), Richard Robson (University of Melbourne, Australia) and Omar M Yaghi (University of California, Berkeley, USA). The Royal Swedish Academy of Sciences that has decided the award of the Nobel prize to Chemistry 2025 commented that the molecular architecture of Metal Organic Frameworks (MOFs) contains rooms for Chemistry. The typical process parameter and outcomes as well as the reusability of the Zr-based MOFs as catalysts for the production of biodiesel were exemplified. MOFs and their derivatives were suggested to be the smart catalysts for the bright biorefinery facilities in near future.</p>	41
9	<p>The review by Anoop Singh and coworkers is focused essentially on the new approaches, feedstock and technologies for the sustainable production of biodiesel at the upcoming biorefinery facility. Development of the genetically modified and bioengineered feedstock (plants, yeast, algae, and plant based wastes) is suggested as a promising and sustainable alternative feedstock for enhanced lipid content in cellulose based crops. Significance of life cycle assessment for adoption of biodiesel at the commercial scale is highlighted.</p>	42

10	Jose C S dos Santos and coworkers have conducted a comprehensive bibliometric analysis of the worldwide research (collaborations and output and feedstock) in the field of biodiesel by considering 4586 outputs for over a period of 12 years (2010-2021). The output indicated that China, Malaysia, and India were the prolific publishers with the highest output of scholarly works on biodiesel. The research conducted highlighted the challenge with the sustainability of the feedstock from the environmental and economic perspectives. The use of sewage is suggested to be a promising feedstock for biodiesel production with the least environmental damage. For some specific reasons, most of the researchers opted for the national collaborations and the research was mainly devoted to the feedstock for biodiesel production.	43
11	The review of Omojola Awogbemi's group is focused on the use of tubular reactor technologies for the accelerated production of biodiesel. Tubular reactor technologies were proposed as the most suitable systems to be adopted at the commercial scale for the process intensification. Emphasis was laid on the possible feedstock, catalysts and the conversion process in the tubular reactors. A comparison of various reactor designs like the packed bed, fluidized bed, trickle bed, oscillatory flow and micro-channel tubular reactor were discussed at length for the large scale, cost effective, ecofriendly, low cost and high quality biodiesel production. The tubular reactor technology is proposed for the transesterification process. Moreover, it was highlighted that novel technologies based on robotics, machine learning, artificial intelligence, smart metering should be integrated with the tubular reactor technology for the profitable biodiesel production process at the biorefinery facility.	44

**Table 2:** Highlights of the 11 landmark papers published in the special issue on "Accelerated production of biodiesel" [34-44].

### Recommended technology for the accelerated and large scale production of biodiesel

It is proposed that biodiesel could be produced at a rapid pace using microwave irradiation and a solid acid catalyst in a continuous flow process. Integration of Artificial intelligence (AI) with day to day life is the current trend in scientific research. AI is influencing almost all areas of human activity, namely, transportation, communication, health, climate, energy, education, communication, research and development and innovation in

technology. The newness of the innovative use of AI based machine learning tools to optimize the biodiesel production process using waste cooking oil as the feedstock and microwave irradiation as the mode of activating the substrate and catalyst species should be recognized for the accelerated production of biodiesel that could cater to the demand. The biodiesel thus produced is a suitable and sustainable alternative to the fossil based fuels in the transportation sector. Moreover, the use of biodiesel contributes to lowering of CO<sub>2</sub> footprint relative to the fossil based fuels owing to closed carbon-loop operation. Overall, the successful transformation of such new ideas into the product prototype means good health, green environment, advancement of human society and alleviation of suffering of man-kind. Microwave irradiation is known to accelerate the biodiesel

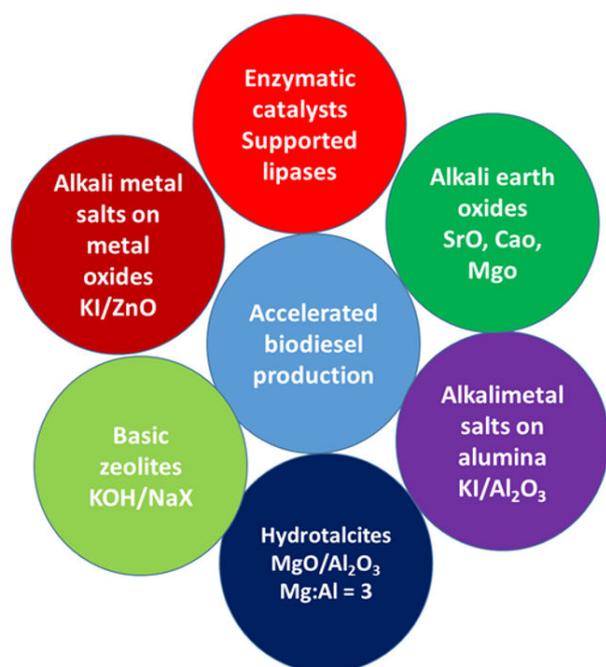
production process. Among various technologies for the biodiesel production from various feedstock, the microwave based activation appears to be the most promising as it ensures sustainability. However, designing the microwave reactor for the large-scale production of biodiesel is a challenge that needs to be addressed.

#### Future directions

The idea of using artificial intelligence based methods for the optimal design of the microwave reactor for the large scale production of biodiesel using waste cooking oil as the feedstock and strontium oxide (SrO) as the solid base catalyst is at its infancy. A viable technology for the demand based supply of biodiesel results in the sustainability in the transportation sector and a great reduction in crude oil imports from Russia which has been an issue of concern between the India and US.

Use of biofuels, especially, biodiesel as fossil fuel substitute, alleviates the catastrophe of climate change [45-49]. Integrating biodiesel production technologies with microwave irradiation, zero waste feedstock like waste cooking oil and exotic solid base catalysts like the SrO and AI and ML holds the key to a breakthrough [50-54].

In brief, the state of the art catalysts developed for the accelerated production of biodiesel were shown in Fig. 2 [55].



**Figure 2:** State of the art catalysts developed for the accelerated production of biodiesel via the transesterification reaction.

For further details on the advantages and disadvantages of various solid base catalysts and new insights the readers are recommended to consult the following references [56, 57]. Thus among various technologies the microwave based heating in synergy with the solid base catalyst SrO, supported on the millimetric silica beads, SiO<sub>2</sub>, namely, SrO/SiO<sub>2</sub>, is outstanding for the rapid conversion of feedstock like waste cooking oil in to biodiesel. Any efforts should be in the direction of scaling up and also

taking the process to the level of commercialization [30-32].

#### CONCLUSION

For attaining the UN sustainable development goals (UN SDGs), namely, good health and well-being (SDG 1), clean energy (SDG 13) and Climate action (SDG 17), it is surmised that there should be paradigm shift from fossil based to bio based resources including biofuels. In this context biodiesel appears to be the most suitable biofuel that could substitute either gasoline or diesel. Microwave irradiation of feedstock in the presence of catalyst is proven to be the best among various technologies for the production of biodiesel at the laboratory scale. Designing the microwave based biodiesel production process that could be adopted at an Industrial scale is the rate determining step in the commercialization of biodiesel. A new design for the microwave technology based biodiesel production from waste cooking oil feedstock using SrO nanoparticles coated on millimetric beads of silica is awaited for the large scale conversion of the feedstock to biodiesel. Any breakthrough leads to clean environment and good health and well-being of mankind.

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#### CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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