Review Article

Ganesan Subbiah, Devanshu J. Patel, Saroj Kumar Acharya, Soumya V. Menon, Damanjeet Aulakh, Krishna Kumar Shukla and Kamakshi Priya Kumar*

State-of-the-art nanocatalysts driving sustainable biofuel production

https://doi.org/10.1515/revic-2025-0033
Received April 9, 2025; accepted August 14, 2025;
published online August 25, 2025

Abstract: Nano-catalysts have emerged as significant entities in enhancing the efficacy and Selectivity of biodiesel production from renewable substrates, such as used cooking oils, animal lipids, and plant-derived fats. In contrast to traditional catalytic agents, nanoparticle-based systems, especially those composed of metal oxides and magnetically recoverable materials, exhibit enhanced surface areas (200–500 m^2/g), accelerated transesterification kinetics, and superior tolerance to free fatty acids, culminating in biodiesel yields that surpass 90 % under less stringent reaction conditions. Recent developments in heterogeneous nanocatalysts have facilitated reusability for as many as 50–100 cycles with negligible deactivation (<2 % per cycle), thus bolstering industrial applicability. Novel advancements in synthesis techniques, encompassing sol–gel and sonochemical methodologies, further diminish energy consumption and augment catalyst stability. Despite the challenges associated with production expenses and scalability, ongoing investigations into multifunctional nanostructures and environmentally benign synthesis routes continue to drive advancements toward economically feasible and ecologically sustainable biodiesel technologies.

***Corresponding author: Kamakshi Priya Kumar**, Department of Physics, Saveetha School of Engineering, SIMATS, Savetha University, Chennai, Tamil Nadu, India, E-mail: drkamu955@gmail.com. https://orcid.org/0000-0002-2423-4675
Ganesan Subbiah, Department of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai, Tamil Nadu, India
Devanshu J. Patel, Department of Pharmacology, Parul University, PO Limda, Tal. Waghodia, District Vadodara, Vadodara, Gujarat, India
Saroj Kumar Acharya, Department of Mechanical Engineering, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India
Soumya V. Menon, Department of Chemistry and Biochemistry, JAIN (Deemed-to-be University), Bangalore, Karnataka, India
Damanjeet Aulakh, Centre for Research Impact and Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura, 140401, Punjab, India
Krishna Kumar Shukla, Department of Physics, Maharishi University of Information Technology, Lucknow, Uttar Pradesh, India

Keywords: nanocatalysts; biodiesel synthesis; transesterification; catalyst characterization; sustainable biofuels

1 Introduction

Biodiesel represents a sustainable and ecologically benign liquid fuel derived from renewable feedstocks, including recycled cooking oils, animal fats, and vegetable oils.[1] It has attracted considerable attention as a viable alternative to conventional fossil fuels due to its biodegradability and reduced emission properties.[2] The predominant technique employed for biodiesel production is transesterification. This process involves the conversion of triglycerides into fatty acid methyl esters (FAMEs) through the action of an alcohol in conjunction with a catalyst.[3,4]

Conventional acid and base catalysts, despite their efficacy, pose several challenges, including the formation of soap, corrosive properties, and the production of considerable wastewater that necessitates neutralization.[5] In contrast, nano-catalysts, specifically metal oxides, magnetic solids, and bio-based solid acid catalysts, exhibit enhanced performance attributed to their elevated surface area, augmented catalytic activity, and improved Selectivity.[6] These attributes promote accelerated reaction kinetics, elevated yields, and superior tolerance to free fatty acids and moisture content.[7]

Numerous investigations, including those conducted by Sami et al. (2022), have documented the efficacy of nanocatalysts in enhancing transesterification efficiency and reducing saponification.[8] Nonetheless, obstacles such as elevated production costs and the imperative for efficient catalyst recovery and reutilization continue to pose significant challenges.[9] Recent advancements in heterogeneous nano-catalysts, encompassing magnetically recoverable systems and bio-derived nanomaterials, have commenced addressing these concerns by enhancing recyclability and economic feasibility.[10]

The objective of this review is to furnish a thorough examination of recent developments in nanoparticle catalysts pertinent to biodiesel synthesis. It encompasses the principal categories of nano-catalysts, their synthesis methodologies, characterization approaches, catalytic mechanisms, and performance evaluation metrics. Furthermore, the review highlights the prevailing challenges and future trajectories in developing effective, economically viable, and scalable nano-catalysts for the sustainable production of biodiesel.

2 Engineered nanostructured catalysts for biodiesel transesterification

Nanostructured catalysts play a crucial role in enhancing the transesterification process of biodiesel due to their high surface area, adjustable physicochemical properties, and exceptional catalytic efficiency. These materials facilitate enhanced reaction rates, improve Selectivity, and offer sustainability advantages.[11] This section outlines four primary categories of nanocatalysts: metal oxides, noble metals, structured porous materials, and carbon-based nanomaterials, while highlighting their performance metrics and the associated challenges.

Figure 1 illustrates the hierarchical classification and functional delineation of nanocatalysts used in the transesterification process for biodiesel production. The schematic delineates fundamental categories, namely, metal oxide, noble metal, structured porous, and carbon-based nanocatalysts, alongside their corresponding catalytic functions, which include base, acid, electron transfer, and support roles. These catalytic mechanisms are integral to pivotal phases in the synthesis of biodiesel, encompassing the activation of triglycerides, the transesterification reaction, and the ensuing processes of product separation and catalyst reusability.

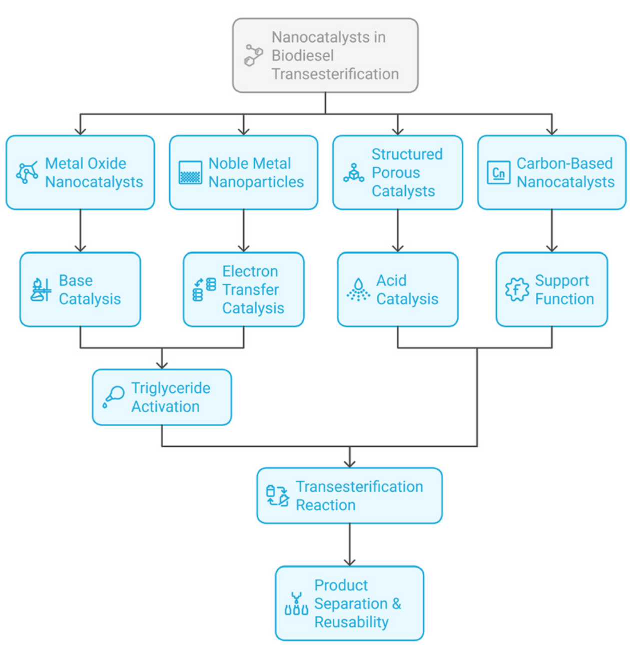

Figure 1: Nanocatalysts in biodiesel transesterification.

2.1 Metal oxide nanocatalysts

Metal oxides, such as MgO, CaO, and ZnO, are extensively employed due to their intrinsic basicity, substantial surface area, and thermal stability. MgO offers robust alkaline sites that significantly enhance the activation of triglycerides and methanol. ZnO presents both acidic and basic sites, thus facilitating transesterification; however, it necessitates cautious handling due to its toxicological properties.[12]

Composites based on CaO, including CaO–SnO_2 and CaO/SrO doped with K_3PO_4, exhibit enhanced activity and stability, yielding biodiesel at rates ranging from 78 % to 92 % under optimized experimental conditions. SrO-doped hybrids also exhibit effective performance attributed to their potent basic characteristics. Nevertheless, these catalysts are susceptible to agglomeration or deactivation over time and often require elevated temperatures to achieve optimal operational efficacy.[13]

2.2 Noble metal nanoparticles

Noble metal nanoparticles, including Pt, Pd, and Au, showcase remarkable catalytic effectiveness as a result of their surface reactivity and electronic architecture. Pt nanoparticles expedite the transesterification process by fostering the activation of alcohol and lipids, with typical loadings varying from 0.5–2 wt.%.[14] Pd nanoparticles bolster kinetics through advantageous electronic configurations.[15] Au nanoparticles confer catalytic stability and Selectivity attributable to quantum-size effects.[16] These catalysts accomplish elevated yields and rapid reaction rates under mild operational conditions; however, their application is constrained by cost and material scarcity, thereby presenting economic challenges for scalability.[17]

2.3 Structured porous catalysts

Zeolites and mesoporous materials (e.g., SBA-15, MCM-41) are esteemed for their well-defined pore architectures, acidity, and high surface area. Zeolites offer microporous crystalline frameworks that facilitate selective catalysis in fixed-bed systems. Mesoporous materials with larger pore dimensions facilitate the accommodation of triglyceride molecules, thereby enhancing both diffusion and conversion efficiencies.[18] The catalytic performance is contingent upon morphology, surface area, and structural integrity. Factors such as pore blockage and the complexity of the synthesis process may adversely affect long-term operational efficacy.[19]

2.4 Carbon-based nanocatalysts

Carbon nanomaterials, including graphene, carbon nanotubes (CNTs), and carbon quantum dots (CQDs), are investigated for their structural integrity, electrical conductivity, and roles as catalytic supports. Graphene enhances thermal conductivity and metal dispersion, whereas CNTs promote efficient mass and electron transport. CQDs exhibit quantum and surface functional characteristics that are advantageous in reactions conducted at room temperature or under photochemical conditions.[20] Frequently utilized as supports, these materials are appealing due to their renewability and recyclability; however, their effectiveness in standalone catalytic functions necessitates further empirical validation.[21]

Table 1 presents a comparative analysis of the operational efficacy and attributes of nanostructured catalysts used in the transesterification process for biodiesel synthesis. This includes essential properties, catalytic functions, contextual applications, advantages, challenges, and pertinent reference data sources. Definitions and units are delineated for performance metrics, including surface area (m^2/g), catalytic yield (%), waste reduction (%), and deactivation rate (% per cycle), thereby ensuring transparency and reproducibility for both experimental and industrial-scale applications.

Recent developments have highlighted an increasing scholarly interest in next-generation hybrid nanocatalysts, including metal–organic frameworks (MOFs), bifunctional composites with integrated acid–base characteristics, and

Table 1: Comparative summary of nanostructured catalysts for biodiesel transesterification.

Catalyst type	Key properties	Catalytic function	Application context	Advantages	Challenges	Ref
MgO, CaO, ZnO	High basicity (pH > 10), thermal stability (up to 600 °C), surface area: 50–150 m^2/g	Provides basic sites for methanol–oil reaction	Batch/continuous reactors	Inexpensive, readily available, reusable	Agglomeration, leaching, requires T > 60 °C	[22]
$CaO–SnO_2$/ $SrO–K_3PO_4$	Synergistic catalytic sites, enhanced stability, yield: 78–92 %	Improves triglyceride conversion under mild conditions	Heterogeneous solid catalyst beds	High yield, strong basicity, regenerable	Complex synthesis, moderate recyclability	[22]
Pt, Pd, Au NPs	Noble metal surfaces with high dispersion (2–5 nm), 0.5–2 wt.% loading	Activates alcohol and triglyceride molecules at low temperature	Microreactors, hybrid catalyst systems	High selectivity, superior activity at low temperature	High cost, rare availability	[23]
Zeolites (e.g., ZSM-5)	Microporous aluminosilicate, acidity: 0.2–0.8 mmol/g, surface area: 300–400 m^2/g	Acid-catalyzed esterification and transesterification	Waste oil feedstock processing	Stable structure, recyclability, suitable for acid-catalysis	Limited pore size, deactivation by coke formation	[24]
Mesoporous (SBA-15)	Large pore size (4–10 nm), surface area: 500–800 m^2/g	Facilitates diffusion of bulky triglyceride molecules	High-viscosity oil feedstocks	High surface area, better mass transport	Synthesis complexity, moisture sensitivity	[25]
Graphene, CNTs	Conductive, layered or tubular carbon; surface area: 200–1,200 m^2/g	Catalyst support enhances heat and mass transfer	Hybrid nanocatalyst systems	Renewable, recyclable, thermally stable	Requires surface functionalization	[26]
CQDs (carbon quantum dots)	Nanodots <10 nm, high photoluminescence, surface functional groups	Supports photo- or ambient-temperature catalysis	Emerging photo-biodiesel systems	Renewable, operates under mild conditions	Low maturity, reproducibility issues	[27]
Waste reduction (%)	% Decrease in soap and glycerol waste during processing (usually 10–30 %)	Indicates cleaner process with less byproduct	Industrial sustainability metric	Reduces water treatment costs, increases process efficiency	Dependent on feedstock and operating condition	[28]
Deactivation rate (%/cycle)	% Loss in catalytic activity per reuse cycle (typically 3–10 %)	Measures catalyst recyclability and long-term stability	Catalyst reuse planning	Helps assess lifecycle and cost effectiveness	Higher for unsupported nanoparticles or under harsh conditions	[29]

magnetically recoverable systems. These innovative materials provide enhanced catalytic efficacy, superior compatibility with feedstocks, and facilitate the simplification of post-reaction separation processes. Their adjustable porosity and specific surface chemistry render them exemplary candidates for intricate transesterification pathways. As the body of research advances, it is anticipated that these systems will assume a pivotal role in the scalable and sustainable production of biodiesel.[30]

3 Nanocatalyst synthesis techniques

The methodology used for synthesis plays a crucial role in determining the morphology, surface area, and catalytic efficacy of nanocatalysts employed in biodiesel production. This section outlines four primary techniques widely used to fabricate nanostructured catalysts: sol–gel processing, precipitation-based synthesis, hydrothermal methods, and sonochemical strategies. Each technique presents unique advantages pertinent to customizing particle size, dispersion, and surface reactivity.[31]

3.1 Sol-gel-derived nanocatalyst fabrication

The sol–gel technique is a multifaceted and widely recognized approach for synthesizing nanomaterials, including metal oxides and composite coatings. In this methodology, metal alkoxides or salts are solubilized in solvents to form a sol, which subsequently undergoes hydrolysis and polycondensation to yield a gel.[32] Upon the processes of drying and calcination, finely dispersed nanoparticles are acquired with a meticulously controlled composition and purity. This method facilitates the generation of materials characterized by high surface areas and uniform pore structures, rendering them suitable for catalytic applications. Furthermore, sol–gel techniques are utilized for the development of corrosion-resistant coatings and catalyst supports in applications such as ethanol steam reforming and water oxidation.[33]

In summary, the sol-gel technique has demonstrated its efficacy as a multifaceted and essential methodology for synthesizing nanomaterials with regulated physicochemical properties. Its capacity to customize particle dimensions, morphology, and surface features renders it significantly relevant across various domains, including catalysis, corrosion resistance, and the development of novel materials. The schematic depiction of the sol-gel procedure is presented in Figure 2.

3.2 Precipitation-based synthesis of metal nanoparticles

Precipitation encompasses the chemical interaction between metal salt precursors and a precipitating agent to generate solid nanoparticles, followed by processes of filtration, washing, and drying. Variants of this technique include conventional precipitation, reverse precipitation, and solvothermal approaches.[34] The parameters governing the reaction, such as pH, temperature, and the choice of precipitant, significantly influence the morphology and crystallinity of the nanoparticles produced. For instance, the synthesis of nano-$Mg(OH)_2$ necessitates the maintenance of pH levels above its isoelectric point to promote effective particle formation. The effects of solvents, exemplified by the ethanol-assisted precipitation of manganese carbonate, are also of paramount importance. Moreover, interactions between

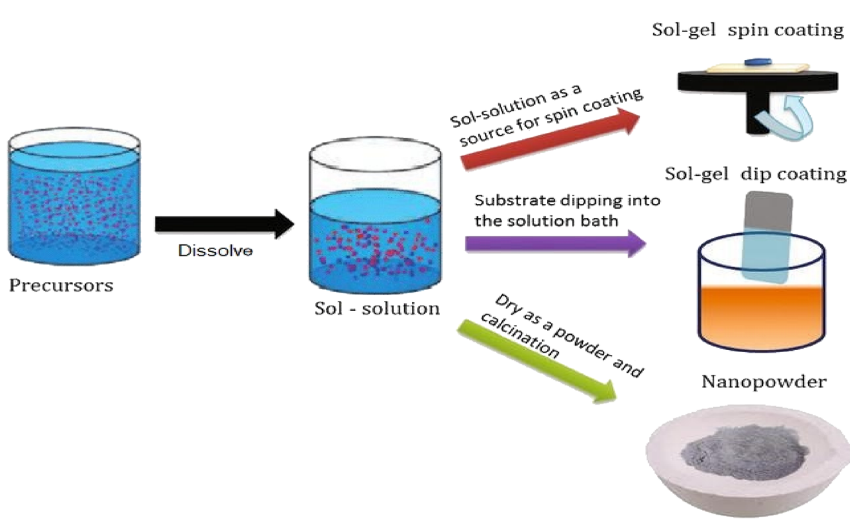

Figure 2: Schematic representation of the sol–gel process used for synthesizing metal oxide nanocatalysts. The illustration outlines the steps of hydrolysis, condensation, gelation, drying, and calcination that lead to the formation of nanoparticles. Not to scale.

metal ions and additives, such as Li^+, during the dehydration of $Mg(OH)_2$, impact the characteristics of the final product.[35]

3.3 Hydrothermal and solvothermal approaches for nanocatalyst engineering

Hydrothermal synthesis involves the reaction of precursors in aqueous environments at elevated temperatures and pressures to produce nanoparticles with high crystallinity and customized size and morphology. This technique is preferred due to its energy efficiency and capability to yield phase-pure materials.[36] Applications of this method span from the utilization of ZnO in biomedical contexts to antimicrobial textiles coated with silver. Despite the requirement for specialized high-pressure apparatus and the handling of corrosive reagents, hydrothermal methodologies are scalable and cost-effective. This approach has also been adapted to fabricate iron oxide, vanadium disulfide, and codoped VO_2 nanomaterials.[37]

3.4 Ultrasound-assisted nanocatalyst synthesis via cavitation mechanisms

Sonochemical synthesis utilizes high-intensity ultrasound to facilitate cavitation, characterized by the generation and subsequent collapse of bubbles, thereby creating localized thermal hotspots that promote the formation of nanoparticles. This non-equilibrium phenomenon enables rapid nucleation, often resulting in nanomaterials with unique morphologies and surface properties.[38] Sonochemistry has been applied to the synthesis of photocatalysts for wastewater remediation, electrode materials for sodium-ion batteries, and environmentally benign pharmaceuticals. Recent *in situ* small-angle X-ray scattering (SAXS) and wide-angle X-ray scattering (WAXS) investigations have enabled real-time monitoring of nucleation and growth processes, thereby enhancing our mechanistic understanding of sonochemically induced nanoparticle formation.[39]

Table 2 Comparative Overview of Nanocatalyst Synthesis Techniques for Biodiesel Applications. This table provides a comprehensive examination of the principal synthesis methodologies employed in the fabrication of nanocatalysts for biodiesel production. It delineates the fundamental characteristics of the processes, the resulting attributes of the nanoparticles, as well as their respective advantages, limitations, and designated application domains. Each synthesis technique is evaluated in terms of its scalability, ecological implications, and suitability for generating catalytically active nanostructures specifically designed for transesterification and associated biofuel synthesis methodologies.

4 Characterization techniques for nanoparticle catalysts

A thorough characterization process is crucial for evaluating the structural composition, morphological properties, and

Table 2: Summary of nanocatalyst synthesis methods for biodiesel applications.

Synthesis method	Key process characteristics	Nanoparticle features	Advantages	Limitations	Relevant applications	Ref
Sol-gel	Hydrolysis and condensation of precursors in solution, followed by drying and calcination.	High purity, tunable particle size, high surface area	Precise control, low-temperature synthesis, homogeneous dispersion	Sensitive to moisture, long processing time	Metal oxide catalysts, corrosion-resistant coatings, hybrid nanocomposites	[40]
Chemical precipitation	Reaction of metal salts with precipitating agents (alkaline, acidic, solvothermal)	Crystalline nanoparticles with controlled phase and morphology	Scalable, low cost, adaptable to various compositions	Sensitive to pH, temperature-dependent morphology, potential for agglomeration	$Mg(OH)_2$, Ca-phosphate, Mn-carbonate, mixed-metal oxides	[41]
Hydrothermal	High-temperature, high-pressure aqueous processing in sealed vessels	Crystalline, uniform particles with well-defined morphologies	Energy efficient, good crystallinity, eco-friendly	Requires specialized equipment, corrosion risks from acidic/alkaline solvents	ZnO, VO_2, Fe_3O_4, MoS_2, hybrid adsorbents, photocatalytic supports	[42]
Sonochemical	Ultrasonic cavitation drives nucleation and growth via localized high pressure and temperature.	Nanostructures with unique shapes, high surface reactivity	Fast synthesis, morphology control, scalable, suitable for green chemistry	Equipment calibration, risk of particle aggregation	Silica particles, AgNPs, CNT composites, drug delivery nanostructures, photocatalysts	[38]

surface attributes of nanoparticle catalysts, as these factors significantly influence their catalytic performance and longevity.[43] The subsequent subsections outline commonly used analytical methodologies within the realm of biodiesel-associated nanocatalyst investigations.

4.1 Crystal structure and phase identification via X-ray diffraction

X-ray Diffraction (XRD) serves as a pivotal tool for elucidating the crystal structure, lattice dimensions, and phase purity of nanoparticle catalysts. This technique yields essential information regarding crystallite dimensions and phase evolution. For instance, Lai et al. (2025) employed XRD to verify the presence of minor secondary phases within $BaTiO_3$ nanoparticles.[44] Furthermore, Demeyere et al. (2024) illustrated the efficacy of XRD in examining the oxidation processes of platinum nanoparticles. The methodology also played a crucial role in characterizing the crystalline properties of cobalt oxide and cadmium sulfide nanostructures.[45] Additionally, XRD demonstrated its utility in tracking phase alterations induced by external factors, including microwave irradiation on vermiculite and crystallization phenomena in polyhedral nanocrystals. Its significance in analyzing strain and lattice imperfections, as evidenced by Davel et al. (2024), underscores its relevance in the study of ion-implanted and defect-ridden materials.[46]

4.2 Surface morphology and topography via scanning electron microscopy

Scanning Electron Microscopy (SEM) constitutes a sophisticated analytical methodology extensively employed to elucidate the surface morphology, geometric configurations, and dispersion attributes of nanoparticle catalysts. This technique provides high-resolution imaging, enabling a comprehensive examination of particle shape, size distribution, and surface texture.[47] SEM has proven to be pivotal in the investigation of a diverse array of materials, encompassing soot nanostructures, nanoparticle-reinforced polymers, and contaminant residues within aquatic systems. Within the domain of biofuel research, SEM plays a crucial role in characterizing nanoparticle–enzyme complexes, identifying particulate emissions, and assessing the structural integrity of catalysts integrated within fly ash-based geopolymer matrices.[48]

In conjunction with SEM, TEM provides an enhanced capability for internal structural analysis of nanoparticles, typically revealing nearly spherical morphologies and average diameters ranging from 10 to 20 nm. These nanoscale characteristics significantly contribute to an increased surface area, enhanced catalytic activity, and uniform dispersion, which are crucial parameters for optimizing transesterification reactions in biodiesel synthesis.[49]

4.3 Atomic-level imaging with transmission electron microscopy

TEM offers unparalleled atomic-level resolution for analyzing nanoparticle catalysts, providing essential insights into parameters such as particle dimensions, crystallinity, and lattice architecture. This methodological approach facilitates the visualization of internal nanostructures and morphological attributes that are inaccessible to traditional microscopy techniques. TEM is particularly adept at discerning lattice fringes, dislocations, and the crystallographic orientation of nanoparticles, which are critical for elucidating their catalytic properties.[50] Recent advancements in TEM, encompassing aberration-corrected imaging and high-angle annular dark-field scanning modalities, have significantly enhanced its capacity to observe atomic configurations and defects directly. Furthermore, the integration of *in situ* and time-resolved imaging methodologies permits the dynamic investigation of nanoparticle behavior under relevant operational conditions. The incorporation of machine learning and image reconstruction algorithms has also substantially improved the interpretation of TEM data, thereby facilitating a more accurate characterization of nanoscale materials employed in biodiesel catalysis.[51]

4.4 Surface area and pore analysis utilizing the Brunauer–Emmett–Teller method

The Brunauer–Emmett–Teller (BET) methodology is indispensable for determining the specific surface area and porosity characteristics of nanoparticle catalysts, which have a direct impact on their adsorption capacity and catalytic efficiency. BET analysis facilitates the estimation of textural attributes through nitrogen adsorption-desorption isotherms.[52] Catalysts characterized by elevated surface area and porosity generally demonstrate enhanced accessibility to active sites and superior transesterification performance. The BET technique has been employed in biodiesel studies to assess mesoporous configurations and refine catalyst design, particularly concerning metal oxides, zeolites, and carbon-based substrates. Its significance is

Table 3: Characterization techniques for nanoparticle catalysts in biodiesel applications.

Technique	Analytical purpose	Key outputs	Advantages	Limitations	Ref
XRD	Determine crystal structure and phase composition	Crystallinity, lattice spacing, phase ID	Non-destructive, highly accurate phase analysis	Limited to crystalline materials	[54]
SEM	Analyze surface morphology and topology	Particle size, shape, dispersion	High-resolution imaging, surface detail	Limited depth information, conductive coating needed	[55]
TEM	Visualize nanostructure at atomic resolution	Lattice fringes, defects, atomic ordering	Atomic-level detail, crystallographic insight	Sample must be ultra-thin; expensive equipment	[56]
BET	Measure surface area and pore size distribution	Specific surface area, pore volume	Critical for catalyst porosity; quantitative	Assumes physisorption only; affected by degassing	[57]

notably amplified when evaluating catalyst efficiency both before and after reuse, thereby aiding lifecycle assessments and reusability evaluations in the development of nanocatalysts.[53]

Table 3 presents a detailed examination of the principal characterization techniques employed for nanoparticle catalysts in the context of biodiesel applications, outlining the analytical aims, key outcomes, operational advantages, and limitations, along with illustrative examples drawn from contemporary scholarly literature.

5 Catalytic mechanisms and performance in biodiesel synthesis

Nanoparticle catalysts have emerged as a crucial component in biodiesel production, primarily by enhancing the transesterification reaction. These catalysts facilitate the interaction between triglycerides and alcohol by providing a high surface area, plentiful active sites, and a diminished activation energy threshold.[58] Characterization methodologies, such as BET analysis, are extensively employed to quantify surface area and porosity, essential attributes that have a direct correlation with catalytic performance. This analytical technique has demonstrated its utility across various disciplines, including nanomaterials and geosciences, for determining the specific surface area of solids.[59]

Depending on their composition and surface architecture, nanoparticle catalysts function through Lewis acid-base mechanisms. Metal oxides, such as CaO or ZnO, serve as Lewis bases, facilitating electrophilic activation, whereas metal nanoparticles operate as Lewis acids, thereby enhancing the activation of nucleophilic species. These mechanistic pathways substantially impact the efficiency, Selectivity, and reusability of catalysts employed in biodiesel synthesis.[60]

5.1 Superior catalytic activity

Nanocatalysts exhibit significantly enhanced activity compared to traditional catalysts due to their nanoscale dimensions and high surface-to-volume ratio. The improved dissociation of alcohol, enabled by γ-Al_2O_3 supports and reduced particle diameters, results in increased biodiesel yields. For example, AuPd nanoparticles and nitrogen-doped carbon-supported metals have demonstrated exceptional activity in various catalytic processes, including biodiesel production.[61] Figure 3 presents a comparative analysis illustrating the biodiesel yield and the reduction of carbon monoxide emissions for various nanocatalysts, thereby highlighting the enhanced efficacy of noble metals and metal oxides in comparison to structured porous materials in terms of catalytic performance and emission mitigation.[61–63]

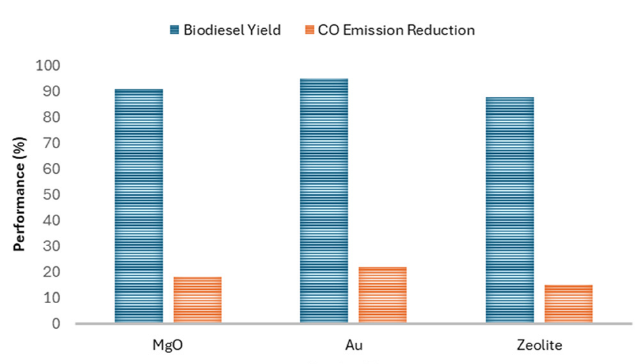

Figure 3: Comparative performance of selected nanocatalysts.

5.2 Enhanced selectivity

The meticulous manipulation of nanoparticle morphology and composition enables customized Selectivity, thereby minimizing side reactions and enhancing the purity of biodiesel. Elevated Selectivity reduces the need for purification processes and enhances overall process efficiency. Nanocatalysts optimized for specific reactions such as the formation of ethyl methyl carbonate exhibit superior Selectivity, making them economically advantageous alternatives amidst fluctuations in fossil fuel markets.[64]

5.3 Stability and durability

Nanoparticles also provide robustness against catalyst deactivation originating from coking, sulfur poisoning, or agglomeration. In contrast to conventional catalysts, they maintain conversion efficiency throughout multiple cycles and under severe conditions. This durability translates into an extended catalyst lifespan and reduces operational costs, thereby facilitating the practical implementation of biodiesel production on a large scale.[65]

5.4 Reduced reaction time and operating temperature

Several nanocatalysts, such as nanocrystalline CaMgZn oxides or lipase-immobilized CeO_2 nanorods, enable expedited reactions at lower temperatures without compromising yield. This decrease in energy requirements promotes process sustainability, while advanced characterization tools, such as XRD, BET, and TEM, validate their structural efficacy.[66]

5.5 Minimized waste generation

The enhanced reaction specificity and efficient feedstock utilization by nanoparticle catalysts substantially diminish the generation of unwanted by-products and waste, even when utilizing suboptimal inputs such as waste oils or tallow. Their contribution to reducing CO_2 emissions and facilitating mild reaction conditions aligns with sustainability objectives.[67] Table 4 elucidates a comparative examination of principal performance indicators, highlighting the distinct advantages of nanoparticle catalysts over traditional catalysts in biodiesel synthesis, including superior yield, increased Selectivity, and enhanced environmental benefits.

Table 4: Comparative performance parameters of conventional versus nanoparticle catalysts in biodiesel synthesis.

Metric	Conventional catalysts[68]	Nanoparticle catalysts[62]	Improvement (%)
Surface area (m^2/g)	100–200	200–500	50–150 %
Biodiesel yield (%)	70–85	90–98	15–28 %
By-products (%)	8–20	<5	50–75 % reduction
Deactivation rate (%/cycle)	5–10	<2	60–80 % reduction
Catalyst lifespan (cycles)	10–20	50–100	400–500 %
Reaction time (hours)	6–8	3–6	40–70 % reduction
Reaction temperature (°C)	60–80	40–60	25–33 % reduction
Waste reduction (%)	–	20–30	N/A
CO Emissions reduction (%)	–	15–25	N/A

6 Challenges and strategic opportunities for nanoparticle catalysts in biodiesel synthesis

Despite significant advancements in nanoparticle-mediated catalysis for biodiesel production, numerous technological and practical obstacles persist. These challenges encompass concerns regarding catalyst deactivation, scalability, cost-effectiveness, and the integration of these technologies into sustainable energy paradigms. Simultaneously, emerging prospects, such as the development of novel nanomaterials, exploration of alternative feedstocks, and integration of renewable energy systems, present promising avenues for addressing existing limitations.[64]

6.1 Catalyst deactivation and regeneration

Catalyst deactivation remains a significant obstacle to achieving consistent catalytic performance in biodiesel synthesis. Phenomena such as fouling, sintering, and chemical poisoning reduce the availability of active surface sites, thereby compromising long-term efficiency and selectivity. A variety of regeneration methodologies have been proposed, including atomic layer deposition, the utilization of sulfur-tolerant catalysts, and the implementation of high-temperature, stable vanadium-based systems. Furthermore, nitrogen-doped carbon and MnOx-based catalysts have demonstrated reversible deactivation characteristics, thereby providing pathways for prolonging catalyst life cycles through periodic regeneration.[69]

6.2 Scalability and synthesis limitations

The translation of laboratory-scale nanocatalyst production to industrial-scale volumes remains a critical bottleneck. Conventional batch synthesis methodologies, which require elevated temperatures and intricate procedural steps, hinder reproducibility and economic feasibility. Emerging methodologies, such as continuous flow reactors, ball milling, and environmentally benign pathways utilizing biomass and non-toxic reagents, are currently under investigation to facilitate the scalable, eco-friendly, and economically viable production of catalytic nanoparticles.[70]

6.3 Cost-effectiveness and material innovation

Economic feasibility remains a pivotal consideration in the industrial implementation of these technologies. Precious metals such as Pd and Au offer exceptional performance; however, they are hindered by substantial costs and stability concerns. Approaches aimed at cost reduction include the development of non-precious metal catalysts (e.g., Cu, Fe, Mn), the use of biomass-derived supports, and the application of magnetic activation. The utilization of autogenic pressure reactors and heterogeneous systems exhibiting high turnover frequencies further decreases the cost per reaction while preserving Selectivity.[71]

6.4 Development of next-generation nanocatalysts

The future success of biodiesel catalysis depends on the rational development of advanced materials. Single-atom catalysts (SACs), flower-shaped Pd nanostructures, and nitrogen-doped carbon systems are currently being investigated for their potential to enhance Selectivity, reusability, and catalytic activity. Innovations such as Fe_3O_4@SiO_2@Pr-NH_2@DAP magnetic nano-catalysts and functionalized carbon-based frameworks have broadened the scope for customizing active sites at the nanoscale, thereby improving transesterification efficiency and the versatility of feedstocks.[72] Table 5 elucidates the primary obstacles encountered in implementing nanoparticle catalysts for biodiesel synthesis and outlines prospective avenues and advancements that may facilitate overcoming these challenges.

Table 5: Challenges and opportunities in the application of nanoparticle catalysts for biodiesel production.[72–74]

Aspect	Challenges	Opportunities/solutions
Catalyst deactivation	Fouling, sintering, and poisoning reduce catalyst life and activity	Atomic layer deposition, regeneration strategies, resistant materials
Scalability	Difficulties in upscaling lab-scale nanoparticle synthesis	Use of flow reactors, ball milling, green synthesis techniques
Cost-effectiveness	High cost of noble metals and synthesis routes	Development of low-cost materials (e.g., biomass-derived), bimetallic and magnetic nanocatalysts
Feedstock flexibility	Limited compatibility with non-traditional or waste-derived oils	Tailored catalysts for high FFA content feedstocks (e.g., microalgae, waste oils)
Integration with renewables	Dependence on fossil-based energy input in production steps	Coupling with solar, wind, or bioenergy systems for greener processing
Environmental impact	Risk of nanoparticle release and toxicity during production or disposal	Development of biodegradable or magnetically recoverable catalysts
Reusability & stability	Loss of activity after a few cycles due to structural breakdown	Enhancing structural integrity through doping or support anchoring

7 Conclusions

Nanoparticle catalysts present a significant opportunity for enhancing biodiesel production by improving reaction efficiency, Selectivity, and environmental sustainability. Their elevated surface area, plentiful active sites, and adjustable properties render them particularly effective, especially in the processing of low-quality or waste-derived feedstocks. Notwithstanding these advantages, obstacles such as catalyst deactivation, limited scalability, and elevated production costs impede large-scale deployment. Addressing these challenges necessitates concentrated innovations in catalyst design aimed at enhancing durability, reusability, and compatibility with industrial applications. Furthermore, integrating nanoparticle catalysis with renewable energy sources, such as solar or wind energy, has the potential to reduce further the carbon footprint associated with biodiesel production. Future investigations should focus on scalable, economically viable synthesis methodologies, expand the range of acceptable feedstocks, and optimize strategies for catalyst regeneration. Through ongoing interdisciplinary collaborations and technological advancements, nanoparticle catalysts are anticipated to play a pivotal role in promoting a sustainable transition in energy systems, thereby contributing to a resilient, low-carbon, and environmentally sustainable future.

Research ethics: Not applicable.
Informed consent: Not applicable.
Author contributions: The authors have accepted responsibility for the entire content of this manuscript and approved its submission.
Use of Large Language Models, AI and Machine Learning Tools: No AI and Mchine learning tools were used.
Conflict interest: The authors states no conflict of interest.
Research funding: None declared.
Data availability: Not applicable.

References

1. Elgharbawy, A. S.; Sadik, W. A.; Sadek, O. M.; Kasaby, M. A. A Review on Biodiesel Feedstocks and Production Technologies. *J. Chil. Chem. Soc.* **2021**, *66* (1), 5098–5109.
2. Alhanif, M. Biodiesel Production: Potential and Future Trends – a Review. *CHEMTAG J. Chem. Eng.* **2023**, *4* (1), 29.
3. Samad, A. A. A.; Shree, R. D. Alternate Fuel Biodiesel. *Int. J. Innov. Res. Dev. Inf. Secur.* **2023**, *09* (03), 168–188.
4. Saravanan, A.; Ragini, Y. P.; Karishma, S.; Hemavathy, R. V.; Jyotsna, M. A Review on Advancing Sustainable Energy: The Role of Biomass and Bioenergy in a Circular Economy. *Sustainable Futures* **2025**, *10*, 100835.
5. Qiu, S.; Wu, Y.; Meng, Y.; Tan, Q.; Gao, X.; Kawi, S. Applications of Al2O3-Based Nano-Catalysts in Thermocatalytic CO2 Transformations: Impacts of Surface Acidity and Basicity. *ChemCatChem* **2023**, *15*. https://doi.org/10.1002/cctc.202300420.
6. Yu, D.; Jiang, Q.; Zhu, H.; Chen, Y.; Xu, L.; Ma, H.; Pu, S. Electrochemical Reduction for Chlorinated Hydrocarbons Contaminated Groundwater Remediation: Mechanisms, Challenges, and Perspectives. *Water Res.* **2025**, *274*, 123149.
7. Yang, H.; Li, G.; Jiang, G.; Zhang, Z.; Hao, Z. Heterogeneous Selective Oxidation over Supported Metal Catalysts: From Nanoparticles to Single Atoms. *Appl. Catal. B Environ.* **2023**, *325*, 122384.
8. Sami, H. Q. ul A.; Hanif, M. A.; Rashid, U.; Nisar, S.; Bhatti, I. A.; Rokhum, S. L.; Tsubota, T.; Alsalme, A. Environmentally Safe Magnetic Nanocatalyst for the Production of Biodiesel from Pongamia Pinnata Oil. *Catalysts* **2022**, *12* (10), 1266.
9. Islam, S.; Basumatary, B.; Rokhum, S. L.; Mochahari, P. K.; Basumatary, S. Advancement in Utilization of Nanomaterials as Efficient and Recyclable Solid Catalyst for Biodiesel Synthesis. *Clean. Chem. Eng.* **2022**, *3*, 100043.
10. Vellaiyan, S. Improved Jatropha Biodiesel Yield and Engine Performance Using Carbon Nanotube- Copper Oxide Nanocatalyst and Ammonium Hydroxide Emulsion for Scalable Clean Energy Solutions. *Biomass Bioenergy* **2025**, *201*, 108120.
11. Wang, A.; Wang, A.; Quan, W.; Zhang, H.; Li, H.; Yang, S. Heterogeneous ZnO-containing Catalysts for Efficient Biodiesel Production. *RSC Adv.* **2021**, *11* (33), 20465–20478.
12. Christopher Selvam, D.; Subbiah, G.; Beemkumar, N.; Juneja, B.; Jena, A.; Devarajan, Y.; Upadhye, V. J. Optimization of Biodiesel Production from Sterculia foetida Seed Oil: Leveraging Non-edible Crops for Sustainable Alternative Fuel. *Results Chem.* **2025**, *16*, 102339.
13. Kiprono, J.; Rutto, H.; Seodigeng, T.; Enweremadu, C. Biodiesel Production Using Calcined Phosphate Rock as a Precursor of Calcium Oxide Heterogeneous Catalyst. *Environ. Clim. Technol.* **2022**, *26* (1), 968–981.
14. Karczmarska, A.; Adamek, M.; El Houbbadi, S.; Kowalczyk, P.; Laskowska, M. Carbon-Supported Noble-Metal Nanoparticles for Catalytic Applications – A Review. *Crystals* **2022**, *12* (5), 584.
15. Xu, R.; Liao, L.; Liang, W.; Wang, H.; Zhou, Q.; Liu, W.; Lu, L.; Fang, B.; Wu, D.; Jin, H.; Li, Y.; Zou, S. Fast Removing Ligands from Platinum-Based Nanocatalysts by a Square-Wave Potential Strategy. *Angew. Chem. Int. Ed.* **2025**, e202509746. https://doi.org/10.1002/anie.202509746.
16. Gangadharan, A.; Goel, P.; Patel, M.; Verma, A. K. Recent Applications of Nanoparticles in Organic Transformations. *Org. Biomol. Chem.* **2022**, *20* (35), 6979–6993.
17. Petel, B. E.; Van Allsburg, K. M.; Baddour, F. G. Cost-Responsive Optimization of Nickel Nanoparticle Synthesis. *Adv. Sustain. Syst.* **2023**. https://doi.org/10.1002/adsu.202300030.
18. Chizallet, C.; Bouchy, C.; Larmier, K.; Pirngruber, G. D. Molecular Views on Mechanisms of Brønsted Acid-Catalyzed Reactions in Zeolites. *Chem. Rev.* **2023**. https://doi.org/10.1021/acs.chemrev.2c00896.
19. Duan, X.; Li, X.; Zhu, B.; Gao, Y.-D. Identifying the Morphology of Pt Nanoparticles for the Optimal Catalytic Activity Towards CO Oxidation. *Nanoscale* **2022**, *14* (47), 17754–17760.
20. Burkholder, M.; Rahman, F.; Chandler, E. H.; Regalbuto, J. R.; Gupton, B. F.; Tengco, J. M. M. Metal Supported Graphene Catalysis: A Review on the Benefits of Nanoparticular Supported Specialty sp2 Carbon Catalysts on Enhancing the Activities of Multiple Chemical Transformations. *Carbon Trends* **2022**, *9*, 100196.
21. Alom, J.; Hasan, M. D. S.; Alam, M. T.; Belhaj, D.; Selvaraj, R.; Hossain, M. A.; Zargar, M.; Ahmed, M. B. Catalytical Performance of Heteroatom Doped and Undoped Carbon-Based Materials. *Catalysts* **2023**, *13* (5), 823.
22. Yuvarajan, D.; Venkata Ramanan, M.; Christopher Selvam, D. Performance Analysis on Mustard Oil Methyl Ester as a Potential Alternative Fuel. *Ind. J. Sci. Technol.* 2016, *9* (37), https://doi.org/10.17485/ijst/2016/v9i37/101982.
23. Milošević, D.; Stevanović, R. M.; Tripkovic, D.; Maksimović, V.; Ćosović, V.; Nikolić, N. D.; Nikolić, N. D. Design of pt-sn-zn Nanomaterials for Successful Methanol Electrooxidation Reaction. *Materials* **2023**, *16* (13), 4617.
24. Zhang, W.; Shi, L.; Xia, W.; Du, Y.; Yao, L. Research on the Anharmonic Effect of Main Reactions of Important Intermediate Species in NH3/DME Mixed Combustion. *Chem. Phys. Lett.* **2025**, *874-875*, 142170.
25. Liu, J.; Du, G.; Chen, T. Synthesis of Ordered Mesoporous Silica with Nonionic Surfactant/Anionic Polyelectrolyte as Template Under Near-Neutral pH Conditions. *Langmuir* **2024**. https://doi.org/10.1021/acs.langmuir.4c01338.
26. Alam, M. W.; Allag, N.; Naveed-Ur-Rehman, M.; Bhat, S. I. Graphene-Based Catalysts: Emerging Applications and Potential Impact. *Chem. Rec.* **2024**, e202400096. https://doi.org/10.1002/tcr.202400096.
27. Jebanisha, B.; Devi, V. N. M. Carbon Quantum Dots: Synthesis, Properties and Multifaceted Applications in Biomedical Imaging,

Environmental Remediation and Sensing Technologies. *Physica Scripta* **2024**. https://doi.org/10.1088/1402-4896/ad98c6.
28. Yasin, M. M.; Khalid, S.; Yasir, M.; Ayub, S. M. I. Advances in Sustainable Chemical Process: Catalysis, Renewable, and Water Reduction. *Indus J. Biosci. Res.* **2025**, *3* (1), 174–184.
29. Afolabi, A.; Chukwuemeka, H.; Igunma, O. Sustainable Catalysis: A Holistic Framework for Lifecycle Analysis and Circular Economy Integration in Catalyst Design. *Eng. Sci. Technol. J.* **2024**, *5* (12), 3221–3231.
30. Madhu, S.; Leo, L.; Prathap, P.; Devarajan, Y.; Jayabal, R. Effective Utilization of Waste Pork Fat as a Potential Alternate Fuel in CRDI Research Diesel Engine – Waste Reduction and Consumption Technique. *Process Saf. Environ. Prot.* 2023, *172*, 815–824.
31. Maripi, S. Nano Catalyst is an Efficient, Recyclable, Magnetically Separable and Heterogeneous Catalyst. *Int. J. Sci. Technol. Eng.* **2024**, *12* (12), 2262–2265.
32. Choudhury, S. A Review of the Sol-Gel Process and its Application. *Int. Educ. Res. J.* **2024**, *10* (7). https://doi.org/10.21276/ierj24449856325648.
33. Fang, Q.; Zhong, R.; Wang, H.; Qi, J. Recent Advances in Doping Engineering of Heterogeneous Catalyst for Carbon Dioxide Hydrogenation. *Mater. Today Chem.* **2025**, *46*, 102770.
34. Ravikumar, C. Unveiling the Formation Mechanism of Polydisperse Iron Oxide Nanoparticles in Coprecipitation Route. *J. Cryst. Growth* **2023**. https://doi.org/10.1016/j.jcrysgro.2023.127419.
35. Rzelewska-Piekut, M.; Nowicki, M.; Regel-Rosocka, M. Precipitation of Pt, Pd, Rh, and Ru Nanoparticles with Non-Precious Metals from Model and Real Multicomponent Solutions. *Molecules* **2023**, *28* (13), 5188.
36. Sun, P.; Lv, Z.; Sun, C. Study on the Synthesis of Nano Zinc Oxide Particles Under Supercritical Hydrothermal Conditions. *Nanomaterials* **2024**. https://doi.org/10.3390/nano14100844.
37. Ejsmont, A.; Goscianska, J. Hydrothermal Synthesis of ZnO Superstructures with Controlled Morphology via Temperature and pH Optimization. *Materials* **2023**, *16* (4), 1641.
38. Matyszczak, G.; Krawczyk, K.; Yedzikhanau, A.; Głuc, K.; Szymajda, M.; Sobiech, A.; Gackowska, Z. Sonochemical Synthesis of Low-Dimensional Nanostructures and their Applications – A Review. *Materials* **2024**, *17* (22), 5488.
39. Zeng, S.; Shui, A.; Yu, H.; He, C. Sonochemical Synthesis of CeO2 Nanoparticles with High Photocatalytic and Antibacterial Activities Under Visible Light. *Int. J. Appl. Ceram. Technol.* **2024**. https://doi.org/10.1111/ijac.14775.
40. Yuvarajan, D.; Venkata Ramanan, M. Investigation on Effect of Magnetite Nanofluid on Performance and Emission Patterns of Methyl Esters of Bio Diesel. *J. Environ. Eng. Landsc. Manag.* 2016, *24* (2), 90–96.
41. Parthasarathy, S.; Behera, S.; Das, D. K.; Patnaik, P.; Das, N.; Mallick, P.; Nayak, S. K. Nanoparticle Synthesis Methods. *Adv. Chem. Mater. Eng. Book Ser.*, 2024, 33–68. https://doi.org/10.4018/979-8-3693-4397-5.ch002.
42. Șchiopu, A.-G.; Iordache, M.; Oproescu, M.; Popescu, L. M.; Ioța, A.-M. Tailoring the Synthesis Method of Metal Oxide Nanoparticles for Desired Properties. *Crystals* **2024**, *14* (10), 899.
43. Kadam, Y.; Solanki, K. N.; Shaikh, M. A.; Savle, A. M.; Malek, N. I.; Mishra, N. Characterization Methods for Nanomaterials. *Adv. Chem. Mater. Eng. Book Ser.* **2024**, 29–60. https://doi.org/10.4018/979-8-3693-6326-3.ch002.
44. Lai, Q.; Xu, F.; Yao, L.; Gao, Z.; Liu, S.; Wang, H.; Lu, S.; He, D.; Wang, L.; Zhang, L.; Wang, C.; Ke, G. End-to-End Crystal Structure Prediction from Powder X-Ray Diffraction. *Adv. Sci.* **2025**. https://doi.org/10.1002/advs.202410722.
45. Appavu, P. Timing on Performance and Emission Characteristics of Palm Biodiesel and Diesel Blends. *J. Oil Palm Res.* 2018, *30*, 674–681.
46. Devarajan, Y.; Madhavan, V. R. Emission Analysis on the Influence of Ferrofluid on Rice Bran Biodiesel. *J. Chil. Chem. Soc.* 2017, *62* (4), 3703–3707.
47. Yardımcı, A. I.; Açıkbaş, Y.; Çapan, R. SEM Images of Carbon Nanotubes (CNTs): Effect of Voltage and Spot Size on Image Resolutions, 2024, *1* (1), 43–51.
48. Verma, M. L.; Dhanya, B. S.; Wang, B.; Thakur, M.; Rani, V.; Kushwaha, R. Bio-Nanoparticles Mediated Transesterification of Algal Biomass for Biodiesel Production. *Sustainability* **2023**. https://doi.org/10.3390/su16010295.
49. Neumann, S.; Rafaja, D. Correlative Multi-Scale Characterization of Nanoparticles Using Transmission Electron Microscopy. *Powders* **2024**. https://doi.org/10.3390/powders3040028.
50. Iwai, H.; Nishino, F.; Yamamoto, T.; Kudo, M.; Tsushida, M.; Yoshida, H.; Machida, M.; Ohyama, J. Atomic-Scale 3D Structure of a Supported Pd Nanoparticle Revealed by Electron Tomography with Convolution Neural Network-Based Image Inpainting. *Small Methods* **2023**, e2301163. https://doi.org/10.1002/smtd.202301163.
51. Chao, H.; Venkatraman, K.; Moniri, S.; Jiang, Y.; Tang, X.; Dai, S.; Gao, W.; Miao, J.; Chi, M. In Situ and Emerging Transmission Electron Microscopy for Catalysis Research. *Chem. Rev.* **2023**. https://doi.org/10.1021/acs.chemrev.2c00880.
52. Stahlfeld, K. W.; Belmont, E. BET and Kelvin Analyses by Thermogravimetric Desorption. *Langmuir* **2023**, *39* (25), 8814–8823.
53. Irwansyah, F. S.; Amal, A. I.; Diyanthi, E. W.; Hadisantoso, E. P.; Noviyanti, A. R.; Eddy, D. R.; Risdiana, R. How to Read and Determine the Specific Surface Area of Inorganic Materials Using the brunauer-emmett-teller (BET) Method. *Asean J. Sci. Eng.* **2022**, *4* (1), 61–70.
54. Lopresti, M.; Mangolini, B.; Conterosito, E.; Milanesio, M.; Palin, L. PCA Analysis of in Situ X-ray Powder Diffraction and Imaging Data Shedding New Light on Solid-State Transformations: the Crystallization of Low Temperature Eutectic Mixtures. *Cryst. Growth Des.* **2023**, *23* (3), 1389–1402.
55. Olbert, M.; Neděla, V.; Jirák, J.; Hudec, J. Size and Shape Analysis of Micro- to nano-particles of Quartz Powders Using Advanced Electron Microscopy and Laser Diffraction Methods. *Powder Technol.* **2023**. https://doi.org/10.1016/j.powtec.2023.119250.
56. Yuvarajan, D.; Venkata Ramanan, M. Experimental Analysis on Neat Mustard Oil Methyl Ester Subjected to Ultrasonication and Microwave Irradiation in Four Stroke Single Cylinder Diesel Engine. *J. Mech. Sci. Technol.* 2016, *30* (1), 437–446.
57. Moldovan, A. A.; Maloney, A. G. P. Surface Analysis – From Crystal Structures to Particle Properties. *Cryst. Growth Des.* **2024**, *24*, 4160–4169.
58. Basumatary, S. F.; Das, B.; Das, B. K.; Hoque, M.; Brahma, S.; Basumatary, B.; Patir, K.; Selvaraj, M.; Rokhum, S. L.; Basumatary, S. Recent Advances in Magnetic Solid Catalysts: Synthesis, Stabilization and Application in Cleaner Production of Biodiesel. *Energy Nexus* **2024**, *15*, 100318.
59. Santos, K.; Serpa, J. de F.; Bizerra, V. de C.; Melo, R. L. F.; Sousa, P. G. de; Alexandre, V. S.; Fonseca, A. M. da; Fechine, P. B. A.; Lomonaco, D.; Sousa dos Santos, J. C.; Souza, M. C. M. de. Enhanced Biodiesel Production with Eversa Transform 2.0 Lipase on Magnetic Nanoparticles. *Langmuir* **2024**. https://doi.org/10.1021/acs.langmuir.4c02542.
60. Zhang, D.; Zhang, Y.; Li, H.; Zhang, Y.; Zhang, P. Lewis Acid–Base Pairs Constructed via Lattice Regulation for Ultrafast Catalytic Transfer Hydrogenation. *ACS Sustain. Chem. Eng.* **2025**, *13* (1), 471–481.

61. Li, C.; Di, R. Evaluation of Metal Nanoparticle Synthesis Methods: Green Chemistry and Catalytic Approaches. *J. Computational Intel. Mater. Sci.* **2024**, 142–151. https://doi.org/10.53759/832x/jcims202402014.
62. Farooq, U.; Fiaz, M.; Nawaz, H.; Abdullah, K. M.; Bajwa, Z. A.; Azeem, R.; Ashraf, S.; Sharjeel, M. Bioinspired Synthesis of Novel Different Nanoparticles and its Utility in Biodiesel and Animals Applications. *Haya: Saudi J. Life Sci.* **2024**, *9* (10), 390–396.
63. Mikky, Y. A.; Bhran, A. A.; El-Araby, R.; Gadallah, A. G.; Shoaib, A. M. Optimization of Biodiesel–Nanoparticle Blends for Enhanced Diesel Engine Performance and Emission Reduction. *Processes* **2024**. https://doi.org/10.3390/pr12112471.
64. Vellaiyan, S.; Aljohani, K.; Aljohani, B. S. E.; Reddy, B. R. Enhancing Waste-Derived Biodiesel Yield Using Recyclable Zinc Sulfide Nanocatalyst: Synthesis, Characterization, and Process Optimization. *Results Eng.* **2024**, *23*, 102411.
65. Cao, K.; Ye, R.; Tang, Y.; Liu, F.; Zhao, Y.; Chen, R. C.; Shan, B.; Shan, B. Deciphering the Stability Mechanism of Pt-Ni/Al2O3 Catalysts in Syngas Production via DRM. *Chem. Eng. J.* **2024**. https://doi.org/10.1016/j.cej.2024.151966.
66. Choubey, G.; Gaud, P.; Fatah, A. M.; Devarajan, N. Numerical Investigation on Geometric Sensitivity and Flame Stabilisation Mechanism in H2 Fueled Two-strut Based Scramjet Combustor. *Fuel* **2025**, *312* (1), 106–116.
67. Choubey, G.; Solanki, M.; Patel, O.; Devarajan, Y.; Huang, W. Effect of Different Strut Design on the Mixing Performance of H2 Fueled Two-strut Based Scramjet Combustor. *Fuel* 2023, *351*, 128972.
68. Alahmar, N. M.; Wan Azelee, N. I. B.; Toemen, S. Efficient Biodiesel Production from Waste Cooking Oil Using a Bifunctional Ce/Mn/γ-Al_2O_3 Catalysts. *Dental Sci. Rep.* **2025**, *15* (1). https://doi.org/10.1038/s41598-024-82845-2.
69. Panahi, H. K. S.; Hosseinzadeh-Bandbafha, H.; Dehhaghi, M.; Orooji, Y.; Mahian, O.; Shahbeik, H.; Kiehbadroudinezhad, M.; Kalam, M.D. A.; Karimi-Maleh, H.; Salehi Jouzani, G.; Mei, C.; Guillemin, G. G.; Nizami, A.-S.; Wang, Y.; Gupta, V. K.; Lam, S.; Pan, J.; Kim, K.-H.; Peng, W.; Tabatabaei, M. Nanotechnology Applications in Biodiesel Processing and Production: a Comprehensive Review. *Renew. Sustain. Energy Rev.* **2024**. https://doi.org/10.1016/j.rser.2023.114219.
70. Rizk, M. M. I.; Davies, G. Translating Batch to Flow: New Procedures for Optimizing Iron Oxide Nanoparticle Synthesis. *Matter* **2024**, *7* (8), 2732–2734.
71. Sunmonu, S.; Odeyale, A.; Soebyakto, B. B. Cost Reduction Techniques on Firm Performance of Selected Quoted Manufacturing Companies in Nigeria. *Asian J. Econ. Bus. Account.* **2024**, *24* (12), 507–519.
72. Selvam, D. C.; Munuswamy, D. B.; Subbiah, G.; Nagappan, B. K.; Arora, A.; Mishra, R.; Devarajan, Y. Study on the Effect of Oxygenated Additives in Nicker Bean Biodiesel Blends for Reduced Emissions. *Chem. Afr.* **2025**, *8* (5), 1983–1994.
73. Lei, Z.; Jia, M. Rational Design of Metal-based Nanocomposite Catalysts for Enhancing their Stability in Solid Acid Catalysis. *Chem. Commun.* **2024**. https://doi.org/10.1039/d4cc03414g.
74. Preeyanghaa, M.; Shenoy, S.; Sagayaraj, P. J. J.; Agamendran, N.; Son, S.; Neppolian, B.; Kim, H.; Sekar, K. Scaling up of Photocatalytic Systems for large-scale Hydrogen Generation. *Appl. Phys. Rev.* **2025**, *12* (1). https://doi.org/10.1063/5.0223598.