

Nanotechnology in Chemical Engineering- Applications in Catalysis

Swaraj Bhongade

The Bishop's School Pune,
Maharashtra, India

Eshan Tripathi

Delhi Public School
Maharashtra, India

Adwait Oak

John P. Stevens High School
Edison, USA

Aditya Kumar Sinha

Conestoga High School
Pennsylvania, USA

Neev Raval

ASPAM Indian International School
Sharjah, UAE

Neel Raval

ASPAM Indian International School
Sharjah, UAE

Abstract— This research paper explores the role of nanotechnology in enhancing catalytic efficiency and developing advanced materials with unprecedented properties. Nanocatalysts, characterised by high surface-to-volume ratios and quantum effects, are pivotal in optimising industrial reactions, reducing energy requirements, and enabling environmentally friendly processes. In material science, nanostructured materials such as carbon nanotubes, graphene, and nanocomposites exhibit superior mechanical, thermal, and optical properties, driving innovation in energy storage, functional coatings, and self-healing systems.

I. INTRODUCTION

A. Introduction to Catalysis and Nanocatalysis

Catalysis plays a critical role in the chemical industry, impacting approximately two-thirds of chemical products and nearly 90% of chemical processes. These include homogeneous, heterogeneous, and enzymatic catalysis. Catalysis has become essential to industrial chemistry since the first industrial catalytic process—the synthesis of ammonium in 1913—especially during crises such as the 1970s oil shortage. Its importance extends beyond petrochemicals to environmental protection, as exemplified by catalytic converters introduced by General Motors and Ford in 1974, which mitigate toxic automobile emissions.

Catalysts accelerate chemical reactions by reducing the activation energy and guiding reaction pathways toward desired products. Almost all material types—acids, bases, metals, and organic complexes—can act as catalysts for specific processes. The first systematic study of catalysis, conducted by Jöns Jacob Berzelius in 1836, laid the foundation for understanding catalytic mechanisms.

This review article emphasizes heterogeneous catalysis, where solid catalysts interact with reactants in different phases, such as gas or liquid. Precious metals, including platinum, palladium, and rhodium, play a key role in catalytic converters and industrial processes like hydrogenation and CO oxidation. These metals, often referred to as the platinum group, are

effective due to their ability to form stable nanoparticles, typically 1–100 nm in size. For example, Paul Sabatier's work with nickel catalysts on hydrogenation and Irving Langmuir's CO oxidation studies were pioneering efforts in heterogeneous catalysis.

B. Nanotechnology in Catalysis

Nanotechnology has revolutionized heterogeneous catalysis. Historically, the inability to visualize nanoparticles hindered early catalytic research. However, advancements in electron microscopy over the past two decades have enabled the direct observation of nanoparticles at atomic resolution. This has demystified the so-called "black art" of catalysis and fostered precise control over nanoparticle size, shape, and surface properties.

Nanoparticles are particularly advantageous in catalysis due to their high surface-area-to-volume ratios, which provide more active sites for chemical reactions. This enhances reaction rates, selectivity, and efficiency. Precious metal nanoparticles, such as platinum and gold, are widely used in processes ranging from petrochemical refining to environmental applications like pollutant degradation. These materials can be tailored to specific reactions, enabling innovations in green chemistry and sustainable energy solutions.

C. Advances and Challenges in Nanocatalysis

Modern catalytic science has seen significant advancements in the creation of well-defined nanoparticles. Solution-phase synthesis techniques have enabled precise control over nanoparticle characteristics, facilitating their use in industrial and environmental processes. For example, the development of catalytic converters has drastically reduced vehicle emissions, while nanocatalysts in water purification systems have improved access to clean water.

Despite these advancements, challenges remain. Scaling up the production of nanoparticles for industrial use while ensuring uniformity in their size and catalytic activity remains a significant challenge. Additionally, the high cost of precious metals necessitates the development of alternative materials or efficient recycling methods. Research into theoretical aspects of catalysis and reaction mechanisms is essential to overcoming these challenges and advancing the field.

Catalysis, particularly heterogeneous catalysis using nanoparticles, is at the forefront of chemical engineering innovation. The integration of nanotechnology has transformed this field, enabling more efficient and sustainable chemical processes. As catalytic science continues to evolve, it holds immense potential to address global challenges in energy, environment, and industrial efficiency. Further exploration into the synthesis, scalability, and application of nanocatalysts will be pivotal for the future of chemical engineering. governments to prepare for extreme weather events. In addition, concerning climate change, reliable forecasts play a key role in assessing the effects of global warming, guiding adaptation strategies and making policy decisions related to mitigating its effects.

II. FUNDAMENTALS OF CATALYSIS

Catalysts represent one of the most prominent and earliest examples of nanomaterials in widespread applications. Fundamentally, catalysis operates as a nanoscale phenomenon, enabling chemical transformations by lowering activation energy barriers. Historically, catalysis has been extensively researched; however, it has recently evolved into a nanoscale science that emphasizes molecular-level interactions and precise control of material properties.

Nanomaterial-based catalysts, typically heterogeneous in nature, play a pivotal role in modern catalysis. Their nanoscale dimensions provide an enormous surface area relative to their volume, maximizing active sites exposed to reactants and thus enhancing reaction rates. This principle is fundamental to their efficiency in a range of applications. However, one critical limitation of nanocatalysts is their thermal stability, which decreases with the reduction in crystallite size. The thermal degradation of these materials remains a significant challenge in maintaining consistent catalytic performance under high-temperature conditions.

The field has witnessed significant advancements in characterizing nanocatalysts, particularly metal oxides such as cerium oxide (CeO₂), titanium dioxide (TiO₂), and zinc oxide (ZnO). These materials have been extensively studied for their role in critical catalytic processes like methane combustion and photocatalysis. The integration of mixed oxides and phases introduces additional complexity and offers opportunities to tailor catalytic properties for specific reactions.

Titanium dioxide (TiO₂) is a widely recognized semiconductor and photocatalyst, valued for its versatile applications in areas such as water purification and solar energy conversion. Traditionally, TiO₂ has limited sensitivity to visible light, restricting its efficiency in certain applications. However, hydrogenation has emerged as a promising technique to modify TiO₂ and improve its absorption in the visible light spectrum.

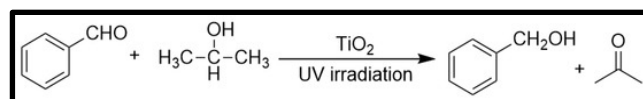


Fig 1. TiO₂ photocatalyzed transfer hydrogenation of benzaldehyde (Ma, D., Zhai, S., Wang, Y., Liu, A., & Chen, C. (2018). TiO₂ Photocatalysis for Transfer Hydrogenation. *Molecules*, 24(2), 330. <https://doi.org/10.3390/molecules24020330>)

This study highlights the importance of several synthesis and processing parameters that influence the hydrogenation of TiO₂ nanomaterials. Critical factors include the synthesis method, as well as the temperature and pressure conditions during the hydrogenation process. These parameters play a vital role in tailoring the properties of TiO₂ nanoparticles by optimizing their interaction with hydrogen. By fine-tuning these conditions, researchers can enhance the photocatalytic activity of TiO₂ and expand its applicability in energy and environmental technologies.

The findings contribute to a broader understanding of how material properties of metal oxides can be engineered through hydrogenation. Such advancements pave the way for developing high-performance photocatalysts tailored for diverse practical applications.

By leveraging advanced analytical techniques, researchers continue to deepen their understanding of how nanostructure, composition, and morphology influence catalytic activity. This insight not only advances fundamental science but also drives the development of more efficient, stable, and sustainable catalytic systems, expanding their applications in energy, environmental remediation, and industrial chemical synthesis.

III. FUTURE PERSPECTIVE ON DECARBONIZATION INITIATIVES

The world is at a critical juncture in its pursuit of sustainable energy solutions. As concerns over climate change and environmental degradation continue to mount, the need for innovative, eco-friendly technologies has never been more pressing. Nanotechnology, with its vast potential for transforming chemical energy production, has emerged as a key player in this endeavor. This article delves into the future prospects and decarbonization initiatives leveraging nanotechnology in chemical energy, focusing on catalysis. Nanotechnology offers several advantages when applied to catalysis for chemical energy production:

A. Increased Surface Area: Nanostructured catalysts have significantly larger surface areas compared to their bulk counterparts. This increase in surface area enhances the catalyst's activity and efficiency.

B. Improved Selectivity: Nanotechnology allows for the precise tuning of catalyst properties, leading to improved selectivity towards desired products and reduced by-product formation.

C. Enhanced Stability: Nanostructured catalysts often exhibit superior stability under reaction conditions, reducing the need for frequent replacement and minimizing waste.

D. Low-Temperature Catalysis: Nanocatalysts can facilitate chemical reactions at lower temperatures, which not only saves energy but also reduces greenhouse gas emissions.

Future Prospects and Decarbonization Initiatives

The future of nanotechnology in chemical energy, particularly in catalysis, is promising. Several decarbonization initiatives are underway, focusing on:

A. Electrochemical Synthesis: Nanotechnology-enhanced electrocatalysts are being developed for efficient CO₂ reduction and water splitting, offering pathways to renewable fuels.

B. Bio-Inspired Nanocatalysts: Researchers are exploring bio-inspired nanocatalysts that mimic nature's efficiency in chemical transformations, potentially leading to more sustainable energy solutions.

C. Nanocatalyst-Based Fuel Cells: Advances in nanocatalysts are crucial for the development of efficient and cost-effective fuel cells, which could significantly reduce our reliance on fossil fuels.

IV. PREFERENCE OF HETEROGENEOUS NANOCATALYSTS OVER HOMOGENEOUS NANOCATALYSTS

Heterogeneous catalysts offer significant advantages over homogeneous catalysts, particularly in commercial applications, due to their easier recovery and reuse. These features make heterogeneous catalysis an attractive option for various industrial processes. However, practical challenges persist, especially in the context of aerobic oxidation of alcohols. Despite their benefits, heterogeneous catalysts often exhibit lower catalytic activity and are prone to deactivation during reactions.

The challenges associated with heterogeneous catalysts in alcohol oxidation include issues related to active site accessibility and stability. The solid catalyst's structure may limit the interaction between the reactant and the catalytic

surface, affecting efficiency. Furthermore, deactivation occurs due to factors such as catalyst poisoning, structural changes at elevated temperatures, or leaching of active comprised transition metal nanoparticles, such as palladium, platinum, and gold on oxide or carbon supports, which have shown significant promise. These systems provide high dispersioonents.

Nevertheless, materials science and nanotechnology advancements have led to the development of more efficient heterogeneous catalysts. Support of active sites and enhanced activity for aerobic alcohol oxidation under mild conditions. [1]

Recent research has focused on optimising the design of catalysts to overcome limitations. For instance:

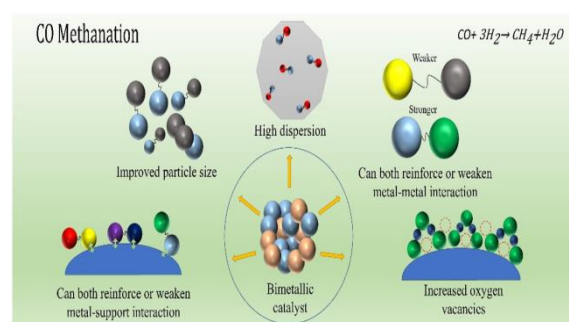


Fig 2. The role of bimetallic catalysts in CO methanation ("A review on recent bimetallic catalyst development for synthetic natural gas production via CO methanation," International Journal of Hydrogen Energy, vol. 47, no. 72, pp. 30981–31002 doi:10.1016/j.ijhydene.2021.10.213.)

Bimetallic Catalysts: Combining two metals, such as palladium and gold, creates synergistic effects that improve catalytic activity and stability.

Core-Shell Structures: Encasing active metals within protective shells enhances durability and prevents deactivation.

Functional Supports: Utilizing advanced support materials, like mesoporous silica or graphene, improves reactant diffusion and catalytic performance.

Although this field is evolving, reviews have comprehensively explored the mechanisms and applications of these heterogeneous catalytic systems in liquid-phase alcohol oxidation. Researchers and practitioners can refer to these authoritative studies for detailed insights into catalyst design, reaction mechanisms, and emerging trends. Continued innovation in this domain holds the potential to resolve existing challenges and expand the commercial applicability of heterogeneous catalysts.

V. GREEN CHEMISTRY AND ENVIRONMENTAL APPLICATIONS OF NANOCATALYSTS

Heterogeneous catalysts play a pivotal role in advancing green chemistry principles by enabling efficient and environmentally friendly chemical transformations. Their unique properties and versatility make them indispensable for various applications aimed at reducing pollution, conserving energy, and minimizing waste. Here are some key areas where heterogeneous catalysts contribute to green chemistry and environmental protection:

A. Reduction of Pollutants

Catalytic Converters: Heterogeneous catalysts, such as platinum, palladium, and rhodium, are used in catalytic converters to reduce harmful emissions from vehicles by converting CO, NO_x, and hydrocarbons into less toxic CO₂, N₂, and water.

Water Treatment: Metal-oxide catalysts like TiO₂ and ZnO are widely employed for photocatalytic degradation of organic pollutants in wastewater, breaking them down into harmless byproducts under light.

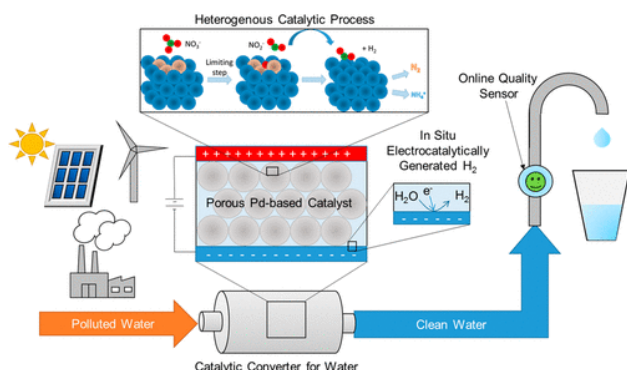


Fig 3. Revolutionizing Water Purification: Heterogeneous Catalysis with Porous Pd-Based Systems and In-Situ Hydrogen Generation ([2]K. N. Heck, S. Garcia-Segura, P. Westerhoff, and M. S. Wong, "Catalytic Converters for Water Treatment," Accounts of Chemical Research, vol. 52, no. 4, pp. 906–915, Feb. 2019, doi: 10.1021/acs.accounts.8b00642.)

B. Renewable Energy and CO₂ Utilization

Methanation and Fuel Production: Heterogeneous catalysts facilitate CO₂ methanation and Fischer-Tropsch processes, aiding in converting CO₂ into valuable fuels, thereby reducing greenhouse gases and promoting a circular carbon economy.

Electrochemical Applications: Catalysts such as metal nanoparticles and carbon-based materials support hydrogen production through water splitting and fuel cell technologies.

C. Green Synthetic Pathways

Biomass Conversion: Catalysts like zeolites and metal oxides convert biomass into biofuels and valuable chemicals, offering sustainable alternatives to fossil fuels.

Solvent-Free Reactions: Heterogeneous catalysts enable reactions in the absence of harmful organic solvents, aligning with green chemistry goals.

D. Waste Minimization:

Selective Catalysis: These catalysts are highly selective, reducing unwanted byproducts and waste. For example, selective oxidation using supported transition metals leads to higher yields and reduced residues.

E. Reusability and Stability: Heterogeneous catalysts can be easily recovered and reused, reducing material consumption and waste.

F. Photocatalysis for Environmental Cleanup

Air Purification: Photocatalysts like TiO₂ remove airborne pollutants such as volatile organic compounds (VOCs) and nitrogen oxides (NO_x).

G. Oil Spill Mitigation: Catalytic materials are being explored to degrade hydrocarbons from oil spills, offering an eco-friendly cleanup method.

H. Sustainable Chemical Manufacturing

Ammonia Synthesis: Iron-based catalysts are crucial for the Haber-Bosch process, which has been optimized to lower energy consumption.

Green Oxidation Processes: Reactions using hydrogen peroxide as an oxidant, catalyzed by metal-organic frameworks (MOFs) or nanoparticles, generate water as the only byproduct.

I. Decarbonization Initiatives

Carbon Capture and Storage (CCS): Functionalized solid catalysts are employed to capture CO₂ from industrial emissions, enabling its reuse or storage.

Catalytic Hydrogenation of CO₂: The conversion of CO₂ into methanol or other chemicals is promoted by heterogeneous catalysts, aiding in carbon recycling efforts.

J. Energy Efficiency

Heterogeneous catalysts often operate under milder conditions compared to traditional processes, reducing energy input and operational costs, and further aligning with green chemistry principles.

Future Prospects

Emerging advancements in heterogeneous catalysis, such as the development of single-atom catalysts, nanoscale catalysts, and bioinspired materials, hold immense promise for addressing environmental challenges. The integration of computational modeling and AI in catalyst design is expected to optimize their performance and sustainability further.

B. Chemical Vapor Deposition (CVD):

Chemical Vapor Deposition (CVD) is a widely used synthesis method for producing high-purity nanomaterials, including carbon-based structures and ceramic thin films. It involves the reaction of gaseous precursors, resulting in the deposition of solid materials on a substrate. CVD is especially valued in industries like semiconductors and ceramics due to its ability to precisely control parameters such as temperature, pressure, and gas flow, enabling tailored material properties.

Catalyst Enhanced Chemical Vapor Deposition (CECVD): This variant utilizes metal catalysts to enable deposition on thermally sensitive substrates at lower temperatures, ensuring high purity and broadening the scope of applicable materials.

Catalytic Chemical Vapor Deposition (CCVD): CCVD is instrumental in the mass production of carbon nanotubes (CNTs). Hydrocarbon vapors are catalytically decomposed using metals like cobalt, nickel, or iron, making it an efficient and cost-effective method for CNT synthesis.

Recent advancements in CVD have improved the growth of two-dimensional (2D) materials, such as graphene. Large-area monolayer graphene films can now be produced on substrates like copper and nickel, paving the way for innovations in electronics and materials science.

VI. INDUSTRIAL APPLICATIONS OF NANOCATALYSIS

A. Nanocatalysts in Energy Production

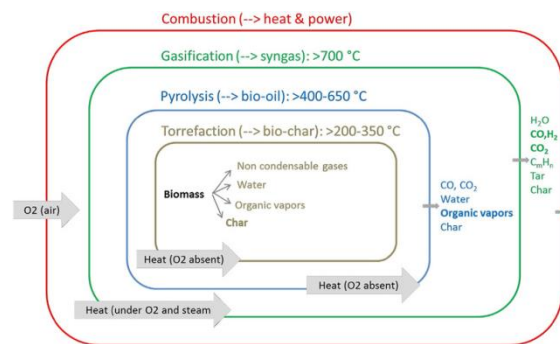
Nanocatalysts play a transformative role in energy production, particularly in environmentally sustainable technologies:

Fuel Cells: Nanoparticles of platinum, palladium, and other metals are widely used as catalysts in fuel cells. These nanocatalysts improve the efficiency of reactions like the oxygen reduction reaction (ORR) and hydrogen oxidation reaction (HOR), enabling the generation of clean energy with reduced material costs. Advances in bimetallic and core-shell nanoparticles further enhance catalytic activity while lowering the reliance on rare metals.

B. Biofuel Production: The increasing demand for renewable and alternative energy sources is driven by the urgent need to address the climate change impacts of fossil fuels on the Earth's atmosphere. Among the various renewable energy forms, bioenergy has emerged as a key contender to replace conventional fossil-based fuels. Biofuels, derived from biological processes like agricultural biomass or anaerobic digestion of solid and liquid waste, provide an eco-friendly alternative to traditional fossil fuels by reducing net carbon dioxide emissions and minimising sulfur output.

Advanced technologies for large-scale biofuel production must be developed to integrate biomass into the current energy framework effectively. Biomass-to-biofuel conversion relies primarily on two methods: thermochemical and biochemical processes.

Thermochemical Conversion: This method produces biofuels such as bioethanol, biodiesel, bio-oil, bio-syngas, and biohydrogen. Key processes include fast pyrolysis, liquefaction, combustion, and gasification. Catalytic liquefaction, a variant of hydrothermal liquefaction, employs catalysts to lower residence time, operating temperatures, and pressure, enhancing the quality of liquid products. Thermochemical biofuels have gained significant attention due to their technical advantages, compatibility with existing industrial infrastructure, and versatility in utilizing diverse biomass types without major process modifications.



The thermal conversion of biomass under different conditions, categorised by their temperature ranges and products (L. Matsakas, Q. Gao, S. Jansson, and P. Christakopoulos, "Green conversion of municipal solid wastes into fuels and chemicals," Elsevier BV. Accessed: Dec. 12, 2024. [Online]. Available: https://www.researchgate.net/publication/312679682_Green_conversion_of_municipal_solid_wastes_into_fuels_and_chemicals)

Catalytic Processing: Thermal biomass processing at lower reaction temperatures using catalytic methods enables the selective production of a narrow range of products, reducing energy requirements. For biodiesel production, heterogeneous catalysts offer distinct advantages over homogeneous catalysts, such as easier product separation, elimination of quenching steps, and suitability for continuous production processes.

This section focuses on advancements in heterogeneous catalysts for biofuel production, with an emphasis on nanocatalysts. Examples include metal oxide catalysts (e.g., ZnO), metal-supported metal oxide catalysts (e.g., Au-ZnO), alloy catalysts (e.g., Cu-Co), and multi-metal oxide systems (e.g., KF-CaO-Fe₃O₄). These catalysts present promising avenues for optimising biofuel production processes, reducing energy costs, and enhancing efficiency.

Hydrogen Generation: In water splitting and photocatalysis, nanocatalysts like TiO_2 , doped semiconductors, and noble-metal nanoparticles enable cost-effective hydrogen production, a key step toward sustainable energy solutions.

2. Nanocatalysts in the Synthesis of Fine Chemicals and Pharmaceuticals

Nanocatalysis has revolutionized the manufacturing of high-value chemicals and drugs by making processes more selective, efficient, and sustainable:

Fine Chemicals: Nanocatalysts enable precise control over reaction pathways, ensuring the selective synthesis of fine chemicals such as fragrances, flavorings, and dyes. Supported metal nanoparticles and metal-organic frameworks (MOFs) are often used to catalyze oxidation, hydrogenation, and C–C coupling reactions.

Pharmaceuticals: The pharmaceutical industry leverages nanocatalysis for the production of active pharmaceutical

ingredients (APIs). For instance:

Palladium-based nanocatalysts facilitate cross-coupling reactions, such as Suzuki and Heck reactions, crucial for synthesizing complex organic molecules.

Enzyme-mimicking nanocatalysts (nanozymes) enhance biocatalysis, enabling green, high-yield production of drug intermediates.

Nanocatalysts support continuous flow chemistry, improving scalability and consistency in drug manufacturing.

The integration of nanocatalysis into industrial applications not only boosts productivity but also aligns with sustainability goals by minimizing energy consumption, reducing waste, and increasing the atom economy. As nanotechnology advances, the scope of nanocatalysis in these fields is expected to expand, driving innovation across industries.

VII. CONCLUSION

Nanotechnology has undeniably revolutionized catalysis, introducing unprecedented advancements in chemical processes, energy production, environmental protection, and industrial manufacturing. The integration of nanotechnology into catalytic systems has not only enhanced their efficiency but has also opened pathways to sustainable and eco-friendly applications, addressing pressing global challenges.

Nanocatalysts, characterized by their nanoscale dimensions, exhibit unique properties such as high surface-area-to-volume ratios, quantum effects, and tailored active sites. These features have enabled breakthroughs in catalytic efficiency, selectivity, and stability. In energy production, nanocatalysts have been pivotal in hydrogen generation

through water splitting and photocatalysis, enabling the transition to a hydrogen-based economy. They have also enhanced the efficiency of fuel cells and facilitated biofuel production, offering renewable energy solutions while reducing carbon footprints. These innovations contribute significantly to global decarbonization efforts and energy sustainability.

Nanocatalysis has revolutionized the synthesis of fine chemicals and pharmaceuticals in industrial chemistry. Nanocatalysts enable precise reaction control, leading to higher selectivity and yield in processes such as hydrogenation, oxidation, and cross-coupling reactions. This has not only improved the economic viability of chemical manufacturing but has also minimized waste and energy consumption, aligning with the principles of green chemistry. The pharmaceutical industry, in particular, has benefited from nanozyme applications and continuous flow processes, enhancing the scalability and sustainability of drug production.

Environmental applications of nanocatalysis are equally transformative. Nanocatalysts play a crucial role in water purification, air quality improvement, and pollutant degradation. For instance, photocatalysts like TiO_2 and ZnO have been instrumental in breaking down organic pollutants in wastewater, ensuring access to clean water. Similarly, catalytic converters equipped with precious metal nanoparticles have drastically reduced vehicular emissions, contributing to cleaner air and mitigating the impact of urbanization on the environment. Furthermore, advancements in carbon capture and utilization technologies, facilitated by nanocatalysts, are crucial for addressing climate change and achieving circular carbon economies.

Despite these successes, challenges remain. The scalability of nanoparticle synthesis, the high cost of precious metals, and the thermal stability of nanocatalysts are significant hurdles that require innovative solutions. To overcome these limitations, Research efforts focus on developing alternative materials, such as bimetallic catalysts, core-shell structures, and advanced support systems like mesoporous silica and graphene. Additionally, integrating computational modeling and artificial intelligence into catalyst design promises to optimize their performance and broaden their applicability.

Looking ahead, the potential of nanocatalysis to address global challenges in energy, environment, and industrial efficiency is immense. The development of single-atom catalysts, bioinspired materials, and hybrid nanostructures will further enhance the capabilities of catalytic systems. The convergence of nanotechnology, materials science, and chemical engineering holds the key to unlocking novel applications and driving sustainable innovations across industries.

In conclusion, nanotechnology's contributions to catalysis epitomize its transformative potential in science and

industry. Nanocatalysts are shaping a future where technological advancements align with environmental stewardship and sustainable development goals by enabling cleaner processes, renewable energy solutions, and greener chemical manufacturing02222. Continued research and interdisciplinary collaboration will ensure that nanocatalysis remains at the forefront of addressing global challenges, fostering a sustainable and innovative future.

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