

NANOCATALYSIS: NEW DIMENSIONS IN CATALYTIC INDUSTRY

Abstract

Nanocatalysis is a cutting-edge field of catalysis that involves the use of nanomaterials as catalysts for various chemical reactions. Catalysis itself is a process wherein a substance, known as a catalyst, accelerates the rate of a chemical reaction without being consumed in the process. This unique property of catalysts is vital for many industrial processes, including the production of fuels, pharmaceuticals, and chemicals.

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Author

Dr. Abhijeet Kr Shrivastava
Assistant Professor
Department of Chemistry
S.D College Kaler, Arwal
A Constituent unit of Magadh University
Bodhgaya, Bihar, India

I. INTRODUCTION

The application of nanotechnology in catalysis has opened up new dimensions and possibilities, revolutionizing the way reactions are performed and products are synthesized. Nanocatalysts are generally composed of nanoparticles with dimensions ranging from 1 to 100 nanometers, providing a high surface area-to-volume ratio. This increased surface area enhances their catalytic efficiency and makes them more reactive than conventional catalysts. Several key aspects make nanocatalysis stand out as a fascinating and promising area of research:

1. **High Surface Area:** As mentioned earlier, nanocatalysts have an exceptionally high surface area due to their small size and increased surface-to-volume ratio. This feature allows for more active sites, which, in turn, leads to higher catalytic activity.

Nanomaterials, such as nanoparticles and nanocomposites, have extremely small dimensions, typically in the nanometer range (1 to 100 nanometers). Due to their small size, they possess a significantly increased surface area compared to the same amount of material in bulk form. This is because the surface area of a material increases with decreasing particle size.

The high surface area of nanomaterials results from the fact that a substantial portion of the atoms or molecules in the material is located on the surface rather than in the interior. As the size of the particles decreases, the proportion of surface atoms becomes more significant relative to the total number of atoms. For instance, a single nanoparticle of a certain material might have a surface area several orders of magnitude greater than that of a larger particle of the same material.

The high surface area is particularly advantageous in catalysis and various other applications, such as adsorption, drug delivery, and energy storage, for several reasons:

- **Enhanced Reactivity:** A higher number of active sites are available on the surface of nanomaterials, which leads to improved catalytic activity. This increased reactivity is essential for speeding up chemical reactions.
- **Efficient Adsorption:** High surface area allows nanomaterials to adsorb larger quantities of molecules, ions, or gases, making them effective adsorbents for various applications, including water purification and gas separation.
- **Better Contact with Reactants:** In catalysis, the reactants need to come into contact with the catalyst's active sites. The large surface area of nanocatalysts ensures more efficient interaction with the reactants, increasing the likelihood of successful catalysis.
- **Optimization of Properties:** The ability to tailor the size, shape, and composition of nanomaterials allows researchers to optimize their properties for specific applications, including catalysis.

- **Energy Storage:** High surface area is beneficial in energy storage applications, such as batteries and supercapacitors, where more surface area can accommodate greater quantities of charge-storing materials.
- **Drug Delivery:** Nanoparticles with high surface area are advantageous in drug delivery systems, as they can carry more drug molecules on their surface, increasing drug-loading capacity.

Overall, the high surface area of nanomaterials and nanocatalysts plays a crucial role in their exceptional performance in various applications. It enables better reactivity, improved efficiency, and enhanced functionality, making them highly desirable materials for advancing technology in diverse fields.

2. **Tunable Reactivity:** The properties of nanocatalysts can be tailored and finely tuned by adjusting their size, shape, and composition. This level of control over the catalyst's structure enables researchers to optimize catalytic reactions for specific processes.

Tunable reactivity refers to the ability to adjust or control the catalytic activity of a material, typically a catalyst, by modifying its properties or environment. In the context of nanocatalysis, the term "tunable reactivity" emphasizes the unique capability of nanomaterial-based catalysts to finely tune their catalytic performance for specific chemical reactions and applications.

The tunable reactivity of nanocatalysts is made possible by several factors:

- **Size and Shape:** Nanocatalysts can be synthesized with precise control over their size and shape. The size of nanoparticles, for example, can be adjusted within nanometer ranges, influencing their surface area and the exposure of active sites. Smaller nanoparticles generally have higher surface area, leading to enhanced reactivity.
- **Composition:** The chemical composition of nanocatalysts can be tailored by choosing different materials or combinations of materials. Each material may exhibit unique catalytic properties, making it possible to select catalysts that are best suited for a specific reaction.
- **Surface Modification:** The surface of nanocatalysts can be functionalized or modified with different chemical groups or ligands. These modifications can alter the electronic properties of the catalyst and its interaction with reactant molecules, thus affecting the catalytic activity.
- **Support Materials:** Nanocatalysts can be supported on various materials, such as metal oxides or carbon nanotubes. The choice of support material can influence the stability, dispersion, and accessibility of active sites, allowing for control over the catalyst's behavior.
- **Reaction Conditions:** The reactivity of nanocatalysts can be influenced by adjusting reaction conditions, such as temperature, pressure, and solvent. Certain nanocatalysts

may exhibit enhanced activity under specific conditions, enabling the optimization of reaction parameters.

- **Alloying and Doping:** Nanocatalysts can be engineered as alloys or doped with other elements, which can significantly modify their electronic structure and catalytic properties.

By fine-tuning these aspects, researchers can design nanocatalysts with specific catalytic capabilities, including improved selectivity, increased reaction rates, and even the ability to catalyze previously challenging reactions.

The ability to control the reactivity of nanocatalysts is essential for tailoring their performance to meet the requirements of different industrial processes. It also contributes to the concept of "precision catalysis," where catalysts are optimized to carry out reactions with high efficiency, minimal waste, and reduced energy consumption.

Tunable reactivity is a central theme in the field of nanocatalysis, and ongoing research aims to develop innovative nanomaterials with even greater control over their catalytic properties. As this area of research advances, nanocatalysis holds significant promise for transforming the landscape of chemical and industrial processes, leading to more sustainable and efficient technologies.

3. **Improved Selectivity:** Nanocatalysts often exhibit better selectivity, which means they can favor the formation of a specific desired product while minimizing unwanted byproducts. This selectivity is essential in reducing waste and improving the overall efficiency of chemical processes.

One of the key advantages of nanocatalysts is their ability to enhance the selectivity of chemical reactions. Selectivity refers to the catalyst's ability to favor the formation of a specific desired product while minimizing the formation of unwanted byproducts. Improving selectivity is crucial in reducing waste and increasing the efficiency of chemical processes, especially in the production of fine chemicals, pharmaceuticals, and other valuable compounds.

The high surface area and unique properties of nanocatalysts contribute to their improved selectivity in several ways:

- **Size and Shape Effects:** The size and shape of nanocatalysts can influence their catalytic activity and selectivity. Different crystal facets and arrangements on the surface of nanocatalysts may expose distinct active sites, leading to varied catalytic behavior for specific reactions.
- **Surface Reactivity:** The high surface area of nanocatalysts allows for more active sites to interact with the reactant molecules. As a result, specific pathways leading to the desired product can be favored, while alternative pathways leading to undesired byproducts are suppressed.

- **Electronic and Geometric Effects:** The unique electronic properties of nanoparticles, often arising due to quantum confinement effects, can influence the reaction mechanism and the formation of specific reaction intermediates, affecting the overall selectivity.
- **Alloying and Doping:** By alloying or doping nanocatalysts with other elements, their catalytic properties can be finely tuned. This includes modifying the adsorption and activation energies for different reactants, thus controlling the reaction pathway and selectivity.
- **Support Materials:** Nanocatalysts supported on specific materials can exhibit improved selectivity. The support can influence the accessibility of active sites and alter the reaction environment, leading to a more selective catalytic behavior.
- **Shape-Selective Catalysis:** Some nanocatalysts with well-defined shapes, such as nanocages or nanocubes, exhibit shape-selective catalysis. These catalysts can selectively accommodate certain reactants based on their size and shape, leading to enhanced selectivity for specific products.

Overall, the ability to tailor the properties of nanocatalysts allows researchers to design catalysts that are highly selective for specific reactions. This is of particular significance in industries where the synthesis of specific products with high purity is essential. By promoting the formation of desired products and suppressing undesired side reactions, nanocatalysts contribute to more efficient and sustainable chemical processes.

It's important to note that achieving high selectivity is an ongoing challenge in catalysis research, and while nanocatalysts offer promising opportunities, the design and optimization of catalysts for selectivity remain complex tasks. Nonetheless, the advancements in nanocatalysis have shown great potential for addressing selectivity issues and unlocking new possibilities for cleaner and more efficient chemical transformations.

4. **Energy Efficiency:** The high catalytic activity and selectivity of nanocatalysts often lead to reduced reaction times and lower operating temperatures. This can result in significant energy savings compared to traditional catalytic processes.

The energy efficiency of nanocatalysts is a critical aspect that makes them attractive for various industrial processes and applications. Nanocatalysts offer several advantages that contribute to their enhanced energy efficiency compared to conventional catalysts:

- **High Surface Area:** Nanocatalysts have a significantly higher surface area due to their small size and increased surface-to-volume ratio. This high surface area provides more active sites for catalytic reactions, leading to faster reaction rates and reduced energy consumption.

- **Reduced Activation Energy:** The unique properties of nanocatalysts can lower the activation energy required for a chemical reaction to occur. This means that reactions can proceed at lower temperatures, resulting in energy savings and milder reaction conditions.
- **Tailored Catalytic Activity:** The properties of nanocatalysts can be finely tuned, allowing researchers to design catalysts with specific catalytic activity for target reactions. This targeted approach ensures that only the necessary reactions are promoted, reducing wasted energy on side reactions.
- **Improved Selectivity:** Nanocatalysts often exhibit better selectivity, favoring the formation of desired products while minimizing the production of unwanted byproducts. High selectivity means that less energy is wasted on the formation of undesired substances.
- **Enhanced Heat and Mass Transfer:** The small size and high surface area of nanocatalysts facilitate efficient heat and mass transfer during reactions. This promotes better mixing and distribution of reactants, resulting in improved energy efficiency.
- **Catalysis under Mild Conditions:** Some nanocatalysts can facilitate reactions under mild conditions, such as room temperature and atmospheric pressure. Operating at lower energy requirements reduces the need for extensive heating or pressurization.
- **Reduced Wastage:** Due to their improved selectivity, nanocatalysts produce less waste and fewer byproducts. This means that less energy is expended on the disposal or treatment of waste materials.
- **Reusability:** Many nanocatalysts can be easily separated and recovered from the reaction mixture due to their small size and supported nature. The ability to reuse catalysts reduces the overall energy consumption and cost associated with catalyst production.
- **Alternative Energy Sources:** Nanocatalysts play a crucial role in energy conversion processes, such as fuel cells, where they enable the efficient conversion of chemical energy into electricity without combustion, leading to cleaner and more sustainable energy production.

By combining these factors, nanocatalysts contribute to more energy-efficient chemical processes across various industries. The ability to design and synthesize catalysts with enhanced activity, selectivity, and reusability can significantly reduce energy requirements and promote greener and more sustainable chemical processes.

However, it's essential to consider the overall life cycle of nanocatalysts, including their production, use, and disposal, to ensure that the environmental and energy impact is fully understood. As research in nanocatalysis continues to evolve, efforts are made to develop even more energy-efficient and environmentally friendly catalysts to address the challenges of sustainable chemistry and industry.

5. **Green Chemistry:** Nanocatalysis has the potential to promote green chemistry principles by enabling cleaner and more sustainable processes. The improved efficiency and selectivity can lead to fewer toxic byproducts and reduced environmental impact.

Green chemistry, also known as sustainable chemistry, is a branch of chemistry that aims to design and develop chemical processes and products that are environmentally friendly, economically viable, and socially responsible. Nanocatalysts play a crucial role in advancing green chemistry principles due to their unique properties and capabilities.

Here are some ways in which nanocatalysts contribute to green chemistry:

- **Reduced Waste Generation:** Nanocatalysts can improve the selectivity of chemical reactions, leading to the production of desired products with minimal formation of byproducts. This reduces waste generation, making the processes more environmentally friendly.
- **Lower Energy Consumption:** The high surface area and improved reactivity of nanocatalysts often enable reactions to occur at lower temperatures and pressures, reducing the energy required for the reaction, and leading to energy-efficient processes.
- **Solvent-Free and Mild Conditions:** Some nanocatalysts can carry out reactions under solvent-free conditions or in benign solvents, reducing the use of hazardous and environmentally harmful solvents.
- **Renewable Feedstocks:** Nanocatalysts can facilitate the use of renewable feedstocks, such as biomass-derived compounds, in chemical reactions, promoting the development of sustainable and bio-based chemicals.
- **Catalyst Recovery and Reuse:** Many nanocatalysts can be easily recovered and reused multiple times due to their small size and supported nature. This minimizes the consumption of catalysts and reduces the need for continuous production.
- **Noble Metal Replacement:** Nanocatalysts can substitute expensive and scarce noble metals (e.g., platinum, palladium) with more abundant and cost-effective materials, making the catalytic processes economically viable and sustainable.
- **Biodiesel Production:** Nanocatalysts have been employed in the production of biodiesel from renewable resources, such as vegetable oils or animal fats, contributing to cleaner and more sustainable alternative fuels.
- **Pollutant Removal:** Nanocatalysts can be used for environmental remediation, facilitating the degradation of pollutants and toxins present in air, water, and soil.
- **Carbon Capture and Utilization:** Nanocatalysts are being explored for carbon capture and utilization, converting carbon dioxide into valuable products, such as chemicals or fuels, instead of releasing it into the atmosphere.

- **Efficient Water Treatment:** Nanocatalysts can assist in the degradation of organic contaminants in water, improving water quality and treatment processes.

While nanocatalysts offer various green chemistry advantages, it's important to consider potential challenges and risks, such as the potential release of nanoparticles into the environment and their ecological impact. Researchers are continually working to address these concerns and ensure the safe and responsible use of nanocatalysts in green chemistry applications.

In conclusion, nanocatalysts hold significant potential for advancing green chemistry principles by enabling cleaner, more efficient, and sustainable chemical processes. Their unique properties and versatility make them valuable tools for achieving environmentally friendly solutions to global challenges in various industries.

6. **Heterogeneous and Homogeneous Catalysis:** Nanocatalysts can be employed in both heterogeneous and homogeneous catalysis. In heterogeneous catalysis, the nanocatalyst is present in a different phase than the reactants, while in homogeneous catalysis, the nanocatalyst and reactants are in the same phase.

Heterogeneous and homogeneous catalysis are two fundamental types of catalytic reactions based on the phase relationship between the catalyst and the reactants. Nanocatalysts can be utilized in both types of catalysis, each offering distinct advantages and applications:

- **Heterogeneous Catalysis with Nanocatalysts:** In heterogeneous catalysis, the catalyst exists in a different phase (usually solid) from the reactants (usually gas or liquid). Nanocatalysts are particularly well-suited for heterogeneous catalysis due to their high surface area and unique properties. Some characteristics of heterogeneous catalysis with nanocatalysts include:
 - **Supported Nanocatalysts:** Nanocatalysts are often supported on solid materials, such as metal oxides, zeolites, or carbon-based substrates. The support enhances catalyst stability, provides mechanical strength, and facilitates catalyst recovery and recycling.
 - **Enhanced Surface Reactivity:** The high surface area of nanocatalysts increases the number of active sites available for catalysis, leading to improved catalytic efficiency.
 - **Diverse Applications:** Nanocatalysts find applications in various industrial processes, such as petroleum refining, chemical synthesis, environmental remediation, and renewable energy production
 - **Catalytic Converters:** In automotive applications, nanocatalysts are used in catalytic converters to convert harmful exhaust gases into less harmful compounds, reducing air pollution.

- **Hydrogen Production:** Nanocatalysts are used in hydrogen production processes, such as steam reforming and water-gas shift reactions, to generate hydrogen for fuel cells and other applications.
- **Homogeneous Catalysis with Nanocatalysts:** In homogeneous catalysis, the catalyst and the reactants are in the same phase, typically liquid. While nanocatalysts are predominantly used in heterogeneous catalysis, they can also be employed in homogeneous catalytic reactions under specific conditions. Some aspects of homogeneous catalysis with nanocatalysts include:
 - **Nanoparticle Stabilization:** Nanocatalysts used in homogeneous catalysis are typically stabilized in a liquid medium by appropriate ligands or surfactants to prevent aggregation.
 - **Selective Homogeneous Catalysis:** Nanocatalysts can provide unique selectivity in homogeneous catalysis due to their size-dependent electronic and surface properties.
 - **Organic Synthesis:** Nanocatalysts have been explored in organic synthesis for selective transformations, such as C-C bond formation and hydrogenation reactions.
 - **Solution Phase Reactions:** Nanocatalysts may be used in solution phase reactions for specific applications, often requiring controlled particle size and surface properties.
 - **Nanocatalysis in Ionic Liquids:** Nanocatalysts can be used in combination with ionic liquids as a green solvent medium for various reactions.

While homogeneous catalysis with nanocatalysts has exciting potential, it still presents challenges, including catalyst separation and recovery, which can be more challenging compared to heterogeneous catalysis. However, advances in nanoparticle stabilization and catalyst recycling methods continue to make progress in this area.

In summary, nanocatalysts can be employed in both heterogeneous and homogeneous catalysis, offering versatile solutions for a wide range of chemical reactions and applications. Their unique properties, such as high surface area and tunable reactivity, make them valuable tools in advancing various catalytic processes and contributing to the development of more sustainable and efficient chemical technologies.

7. **Multifunctional Catalysis:** Nanocatalysts can be engineered to exhibit multifunctionality, where a single catalyst can promote multiple reactions simultaneously. This versatility can simplify reaction pathways and reduce the need for multiple catalytic systems.

Multifunctional catalysis in nanocatalysis refers to the capability of nanocatalysts to simultaneously promote multiple catalytic reactions or exhibit different catalytic functionalities. This concept is particularly significant as it allows for more efficient and versatile use of a single nanocatalyst in various chemical processes. Multifunctional nanocatalysts can provide several benefits:

- **Simplified Reaction Pathways:** Using a single nanocatalyst with multiple catalytic functionalities can simplify reaction pathways by eliminating the need for separate catalysts for each step. This streamlines the overall reaction process and reduces the number of reaction steps, leading to higher efficiency.
- **Sequential Catalysis:** Multifunctional nanocatalysts can enable sequential catalysis, where one catalytic site facilitates one reaction step, and another site promotes subsequent steps in the reaction sequence. This sequential approach can be particularly useful in complex multi-step reactions.
- **Cascade Reactions:** Some multifunctional nanocatalysts can drive cascade reactions, where the products of one catalytic reaction become the reactants for subsequent reactions on the same catalyst surface. This sequential transformation can lead to the formation of intricate and valuable products in a single step.
- **Atom Economy:** Multifunctional catalysis enhances atom economy by minimizing the need for excess reagents and reducing waste generation. This aligns with green chemistry principles, making nanocatalysis more sustainable.
- **Efficient Energy Utilization:** Using a single multifunctional nanocatalyst reduces the energy required for separate catalytic steps, resulting in improved energy utilization and overall process efficiency.
- **Catalytic Diversity:** Multifunctional nanocatalysts can perform diverse types of reactions due to their tunable reactivity and unique surface properties, allowing them to be applied in various chemical transformations.
- **Synergistic Effects:** In some cases, the combination of different catalytic functionalities on the same nanocatalyst can lead to synergistic effects, enhancing overall catalytic activity and selectivity.

Examples of multifunctional nanocatalysts include those with multiple active sites or different metal compositions, allowing them to catalyze multiple reactions or carry out different steps within a reaction sequence. Additionally, core-shell nanocatalysts, where a core of one material is surrounded by a shell of another material, can exhibit multifunctionality, with each component contributing to different catalytic processes.

While the concept of multifunctional catalysis in nanocatalysis shows great promise, the design and optimization of such catalysts are still active areas of research. Challenges include controlling the spatial distribution of different catalytic functionalities, ensuring their stability, and understanding how different reactions

might interact on the same catalyst surface. However, as nanocatalysis continues to evolve, multifunctional nanocatalysts hold significant potential to revolutionize chemical processes and pave the way for more efficient and sustainable technologies.

8. Supported Catalysts: Nanocatalysts can be supported on various materials, such as metal oxides, carbon nanotubes, or zeolites, to improve stability and ease of recovery in industrial applications.

Supported catalysts play a crucial role in nanocatalysis, and they are widely used in various industrial and research applications. A supported catalyst consists of nanoscale catalytic particles (nanocatalysts) that are anchored or dispersed on a solid support material. The support provides several advantages for nanocatalysts, enhancing their performance and facilitating their use in heterogeneous catalysis. Here are some key aspects of supported catalysts in nanocatalysis:

- **Stability:** Nanocatalysts, especially those in their isolated form, can be susceptible to agglomeration and deactivation during catalytic reactions. By supporting them on a solid material, the catalyst particles are stabilized, preventing unwanted interactions and ensuring a longer catalyst lifetime.
- **Enhanced Surface Area:** The support material typically has a high surface area itself, which, when combined with the high surface area of the nanocatalyst, provides a large number of active sites for the catalytic reaction. This enhanced surface area increases the efficiency of the catalyst and improves catalytic activity.
- **Control of Particle Size and Distribution:** The support material can help control the size and dispersion of nanocatalyst particles. This control is crucial for optimizing the catalytic performance, as particle size and distribution can significantly influence catalytic activity and selectivity.
- **Catalyst Recovery and Reusability:** Supported catalysts are easy to separate from the reaction mixture due to the solid support, allowing for straightforward catalyst recovery and reuse. This reusability is economically advantageous and contributes to greener and more sustainable catalytic processes.
- **Better Heat and Mass Transfer:** The support material enhances heat and mass transfer during the reaction, promoting efficient mixing and contact between the reactants and catalyst particles. This improves the overall reaction kinetics and reaction rates.
- **Selectivity Control:** The choice of support material can influence the selectivity of the nanocatalyst. The support may modify the catalyst's electronic and surface properties, leading to improved selectivity for specific reactions.
- **Catalyst Protection:** The support material can act as a protective barrier for the nanocatalyst, preventing leaching or unwanted side reactions, and ensuring that the active sites remain accessible and active.

- **Broad Range of Applications:** Supported nanocatalysts find applications in various industries, including petrochemicals, pharmaceuticals, environmental remediation, and fine chemical synthesis.

Common support materials for nanocatalysts include metal oxides (e.g., silica, alumina, titania), carbon-based materials (e.g., carbon nanotubes, graphene, activated carbon), and zeolites. The choice of support material depends on the specific catalytic application and the interactions between the nanocatalyst and the support.

Supported catalysts represent a practical and efficient approach to utilize nanocatalysts in industrial processes. Their ability to enhance stability, control particle size, and enable catalyst recovery makes them valuable tools for advancing catalysis research and promoting sustainable and energy-efficient chemical transformations.

Despite the immense promise of nanocatalysis, some challenges remain, including issues related to catalyst stability, scalability, and potential toxicity concerns. However, ongoing research and development are addressing these challenges and moving nanocatalysis closer to real-world applications.

II. CONCLUSION

Nanocatalysis represents a remarkable advancement in the field of catalysis, offering unprecedented opportunities to revolutionize chemical processes and contribute to a more sustainable and efficient future. As technology continues to progress, nanocatalysis is likely to play a vital role in various industrial sectors, leading to innovative products and processes.

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