

Development and Application of Green Catalysts: Challenges, Optimization, and Future Perspectives

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Abstract. This paper comprehensively reviews the development and application of green catalysts in modern chemical industries, with a focus on analyzing the significant advantages of various types of green catalysts, such as metal-organic frameworks (MOFs) and enzyme catalysts, in improving reaction efficiency, reducing energy consumption, and minimizing by-product generation. The paper delves into the design and synthesis of green catalysts, optimization of reaction conditions, and technologies for catalyst recycling and regeneration, highlighting their key roles in enhancing catalyst performance. Despite challenges such as high material costs, complex synthesis processes, and issues with stability and durability in practical applications, continuous technological innovation and process improvements offer promising solutions. As global attention to sustainable development grows, green catalysts are expected to have broad applications in emerging fields such as carbon capture and utilization, renewable energy conversion, and environmental remediation, thereby driving the green transformation and low-carbon development of the chemical industry and providing strong technical support for achieving global sustainability goals.

Keywords: Green catalysts, Reaction efficiency, Energy reduction, Recycling.

1. Introduction

Chemistry has always played a crucial role in human development, permeating every aspect of our lives. Consequently, the application and advancement of chemistry have garnered widespread societal attention. However, the production and use of chemical products often come with various issues, including but not limited to the incomplete utilization of raw materials, low yields, complex processes, and the generation of numerous by-products. One of the most critical challenges is the toxic and corrosive pollutants and wastes produced by the chemical industry, which exist in various forms across different media, posing serious threats to the environment and human health. Addressing these negative impacts has become essential for problem-solving, leading to the emergence of the green chemistry concept. The core of this concept is to maximize the utilization of materials and energy in reactions while minimizing the total amount of pollutants generated during the process, thereby achieving efficient, environmentally friendly production [1].

Catalysts play an indispensable role in chemical reactions, accelerating reaction rates and reducing by-product formation. However, some traditional catalysts may generate harmful substances and by-products during reactions, reducing yields [2]. Thus, the development and use of green catalysts have become a key approach to realizing green chemistry. This efficient and environmentally friendly approach can maintain the original functions of catalysts while reducing by-product generation, achieving low or even zero emissions of pollutants [3]. With the promotion of green chemistry, many green catalysts have been widely used in industrial production. For example, in the chemical industry, common green catalysts include hydrated talc-based solid base catalysts, inorganic solid bases supported by alumina, and solid base catalysts supported by molecular sieves. In addition, biocatalysis in oil desulfurization is also an important technology [1].

However, green catalysts still face challenges, such as difficulties in separating products, complex synthesis processes, the scarcity of suitable carriers, and limited applicability [4]. This paper focuses on analyzing different types of green catalysts and their effects on chemical reactions to provide references for future research and development.

2. Classification and Characteristics of Green Catalysts

2.1. Metal-Organic Frameworks (MOFs)

Metal-Organic Frameworks (MOFs) are a class of porous materials formed by the coordination of metal ions or metal clusters with organic ligands. Due to their unique structural features, MOFs have been widely applied in various fields, including catalysis, gas storage and separation, and biosensing [5]. The significant advantages of MOFs include high specific surface area, tunable structure, and diverse ligand functionality, making them stand out in catalytic applications. For instance, in alcohol oxidation reactions, MOFs, with their adjustable pore structure and abundant active sites, achieve shape-selective catalysis of reactants, significantly improving reaction efficiency and selectivity [6]. MOFs have broad application prospects in the field of green catalysts. Due to their ability to design and control pore size and shape, MOFs can be customized according to the size and shape of specific reactants, achieving highly selective catalytic reactions. Moreover, the diversity and functionality of MOFs make them advantageous in asymmetric catalysis, gas adsorption and separation, and catalyst regeneration. For example, some MOFs, by introducing functionalized organic ligands, can further enhance catalyst stability and activity, reduce by-product formation, and achieve more environmentally friendly chemical reactions [6].

2.2. Enzyme Catalysis

Enzyme catalysis, as an important branch of green catalysis, has garnered significant attention due to its natural catalytic function in biological systems. The primary advantages of enzyme-catalyzed reactions are their high specificity, mild reaction conditions, and biodegradability, making enzyme catalysis uniquely advantageous in industrial production. For example, enzyme catalysis has been widely applied in the pharmaceutical industry, significantly improving green production levels by reducing the use of chemical reagents and lowering energy consumption [7]. In industrial applications, a notable characteristic of enzyme catalysis is its ability to maintain high catalytic activity even under extreme temperature and pH conditions. This trait makes enzyme catalysis indispensable in the synthesis of complex organic molecules, chiral drugs, and other high-value-added chemicals [8]. Additionally, enzyme catalysis can be optimized through genetic engineering and protein engineering, further improving its catalytic performance and expanding its application range. For instance, scientists have successfully developed enzymes capable of catalyzing non-natural substrates through directed evolution techniques, offering new possibilities for the future development of green chemistry [9].

3. Applications of Green Catalysts in Chemical Reactions

3.1. Improving Reaction Efficiency

Green catalysts have shown great potential in improving the efficiency of chemical reactions. Traditional chemical reactions often rely on harsh conditions such as high temperatures and pressures, which not only increase energy consumption but may also lead to an increase in by-products, thereby affecting reaction selectivity and yield. Green catalysts, with their efficient active sites and tunable reaction pathways, can achieve high-efficiency reactions under mild conditions. For example, in the selective hydrogenation of olefins, using MOFs as catalysts not only significantly improves product selectivity but also reduces unnecessary by-product formation, thereby increasing overall yield [10].

The application of green catalysts in the synthesis of complex molecules has also shown significant advantages. For instance, in the synthesis of chiral drugs, enzyme catalysis, due to its high stereoselectivity, can achieve efficient construction of chiral molecules under mild conditions. Compared to traditional chemical catalysts, enzyme catalysis has a clear advantage in reducing reaction steps and increasing target product yields, thereby significantly enhancing the overall efficiency of chemical reactions. For example, in the synthesis of antibiotics, using enzyme catalysts

for asymmetric synthesis can greatly shorten synthesis routes, reduce energy consumption, and improve product purity [11]. Moreover, the application of green catalysts in polymer synthesis is also noteworthy. Traditional polymerization reactions often require high-temperature and high-pressure conditions, which not only consume large amounts of energy but may also lead to non-uniform polymer structures. By introducing green catalysts, such as enzyme catalysts or MOFs, efficient polymerization can be achieved at room temperature and atmospheric pressure, resulting in high-quality polymer materials. For example, using MOFs catalysts for emulsion polymerization not only improves polymer molecular weight and molecular weight distribution but also significantly reduces reaction temperature and time, thereby enhancing production efficiency and product quality [12].

3.2. Reducing Energy Consumption

Green catalysts have unique advantages in reducing energy consumption. Traditional chemical reactions often rely on high temperatures and pressures to overcome the activation energy of reactants. Although this approach can accelerate reactions, it also leads to high energy consumption. Green catalysts reduce reaction activation energy, allowing chemical reactions to occur at room temperature and atmospheric pressure, thereby significantly reducing energy consumption. For instance, in hydrogenation reactions in organic synthesis, traditionally conducted at high temperatures and pressures, the introduction of MOFs catalysts allows the reaction to proceed smoothly at room temperature, significantly reducing energy consumption [10]. Enzyme catalysis has also shown great potential in reducing energy consumption. Since enzyme-catalyzed reactions typically occur under mild physiological conditions, they avoid the extreme conditions required by traditional chemical reactions. For example, in the biopharmaceutical industry, enzyme catalysts are widely used for large-scale production of drug intermediates. Their advantages include efficient reactions at room temperature and their high specificity and selectivity, which reduce side reactions and subsequent separation and purification energy consumption [13]. Additionally, the application of green catalysts in large-scale industrial production contributes to energy conservation and emission reduction. For instance, in petroleum refining, traditional catalysts often require high-temperature treatment to achieve the desired catalytic effect. However, by introducing new MOFs catalysts, the same reaction effect can be achieved at lower temperatures, saving energy and reducing carbon emissions, which is crucial for environmental protection. This energy-saving effect has broad application prospects in future large-scale industrial applications, especially in energy-intensive industries such as metallurgy and chemicals.

3.3. Reducing By-Products

In chemical reactions, the generation of by-products not only reduces the yield of the main product but also leads to environmental pollution and resource waste. Green catalysts, by improving reaction selectivity, can effectively reduce by-product generation, thereby achieving cleaner chemical reactions. For example, in asymmetric synthesis reactions, enzyme catalysts, due to their high specificity, can strictly control product stereoselectivity, resulting in high-purity target products with minimal by-products. This not only reduces the difficulty of subsequent separation and purification but also significantly lowers waste discharge, reducing environmental pollution [14]. MOFs catalysts have also shown significant advantages in reducing by-product generation. Due to their porous structure and tunable pore sizes, MOFs can selectively adsorb specific reactant molecules, thereby avoiding unnecessary side reactions. For example, in alkylation reactions, MOFs catalysts can control pore size to selectively catalyze the target reactant to produce the desired product while minimizing by-product formation, thus improving overall reaction efficiency and cleanliness [15]. Green catalysts also play an important role in minimizing waste. By reducing by-product generation, green catalysts can reduce waste emissions in chemical reactions, thereby reducing environmental impact. For instance, in the treatment of organic wastewater, biocatalysts can selectively degrade specific organic pollutants, reducing the number of chemical agents used and thereby reducing the risk of secondary

pollution. This characteristic of minimizing waste generation makes green catalysts essential in environmental protection and resource conservation, with broad application prospects.

4. Development and Optimization of Catalysts

4.1. Catalyst Design and Synthesis

Typically, gold nanoparticles (AuNPs) are synthesized using specific reducing agents, including sodium borohydride, thiols, and others. This method usually requires stabilizers to prevent aggregation and ensure stability. However, a more suitable raw material for preparation has recently been discovered—biological carrier JPS. This material reacts more easily, disperses particles, has a large volume and light weight, and does not require the use of various stabilizers, while also possessing good stability. Some functional groups in Jute Plant Sticks (JPS) can generate traditional reducing agents for AuNPs in water, and these functional groups are also activated when heated at 70°C, producing gold nanoparticles by reducing absorbed chloroauric acid (HAuCl₄) solution. Moreover, some of the activated functional groups may also adsorb onto the surface of AuNPs, enhancing their stability, catalytic activity, and recyclability [16]. Nowadays, many new catalysts are gradually entering the public view, with magnetic catalysts being a typical example. These catalysts are magnetic and can be recycled by applying a magnetic field, making them widely used in various fields. For example, magnetic catalysts can avoid some common limitations of traditional catalysts in bioprocessing technology, such as cumbersome pretreatment, filtration, and centrifugation; they can be stirred by a magnetic field instead of mechanical stirring to avoid catalyst degradation; and the use of a magnetically stabilized fluidized bed reactor can improve the reusability of biocatalysts compared to traditional methods. However, the size and heterogeneity of magnetic catalysts tend to increase due to aggregation, which limits the material's application on an industrial scale, and the high cost of manufacturing nanoscale scaffolds also poses a challenge [17].

4.2. Optimization of Reaction Conditions

Carbon dots (CDs), as a new nanomaterial, have shown good performance in hydrogen bond catalysis. However, due to their unique luminescent properties, CDs are mostly used as photocatalysts, often neglecting their catalytic performance under non-photocatalytic conditions. To address this issue, Pirsahab et al. (2018) investigated the catalytic effect of carbon dots on hydrogen peroxide degradation. They used green-synthesized biopolymer-based nano carbon dots (NCDs) as catalysts to study the degradation of phenol in hydrogen peroxide. This new eco-friendly material facilitates the decomposition of hydrogen peroxide and produces hydroxyl radicals. To explore the catalytic ability of NCDs, they conducted a control experiment. In the presence of only the catalyst, phenol was barely adsorbed, but when both the catalyst and hydrogen peroxide were present, the degradation rate of phenol increased significantly. This phenomenon suggests that NCDs do not directly affect phenol degradation but significantly improve efficiency when acting as a catalyst for H₂O₂ [18]. This study indicates that optimizing reaction conditions, particularly the combination of catalysts and reactants, can significantly improve catalytic efficiency. The catalytic effect of NCDs is fully realized in the presence of hydrogen peroxide, demonstrating their potential in environmentally friendly catalytic reactions. This also suggests that in future green catalyst development, attention should be paid not only to the performance of the catalyst itself but also to the optimization and coordination of reaction conditions to maximize catalyst efficiency. By rationally designing reaction conditions, such as temperature, pH, and reactant concentration, green catalysts can exhibit excellent performance in a wider range of chemical reactions. For example, in photocatalytic reactions, in addition to the wavelength and intensity of the light source, optimizing conditions such as catalyst surface modification and solvent selection is also crucial. These optimizations can further enhance catalyst activity and selectivity, achieving more efficient chemical reactions.

4.3. Recycling and Regeneration of Catalysts

In recent years, with the growing global energy demand and worsening environmental issues, the development and application of renewable energy have become top priorities for countries worldwide. However, traditional renewable energies such as solar and wind power are susceptible to natural environmental influences, leading to intermittent and unstable energy supply. In contrast, hydrogen energy, as a long-term energy storage option, offers unique advantages. This clean energy source is an excellent energy carrier with high energy density and can achieve efficient conversion. An important aspect of hydrogen energy development is the application of fuel cells (FCs), which convert chemical energy in fuels directly into electricity through electrochemical reactions in an efficient and environmentally friendly manner. In fuel cells, platinum (Pt) is commonly used as a catalyst to promote redox reactions at the anode and cathode. However, practical applications must consider not only the catalyst's activity but also its recyclability and durability, as these factors affect the cost and lifespan of FCs. Currently known methods to improve the stability of Pt catalysts in ORR include size control, crystal face regulation, alloying, and carrier regulation. For example, researchers have developed high-stability, high-activity catalysts using Co-N-C as the carrier, and other researchers have proposed a high-temperature sulfur anchoring method, utilizing the strong chemical reaction between Pt and S to prepare Pt alloy nanoparticles as catalysts [19].

5. Challenges and Future Directions of Green Catalysts

Although green catalysts have shown great potential in chemical reactions, their development and widespread application still face numerous challenges. First, the synthesis process of green catalysts is often complex, and the high cost of materials limits their promotion in large-scale industrial applications. Particularly in the development of new catalysts such as metal-organic frameworks (MOFs) and nanomaterials, the complexity and reproducibility of synthesis methods have been persistent issues in research. Additionally, achieving efficient recycling and regeneration of catalysts and reducing resource waste remain urgent problems in green catalyst research. Green catalysts also face challenges in terms of stability and durability in practical applications. Although many studies have attempted to enhance catalyst stability and efficiency through alloying, size control, and crystal face regulation, the actual effects of these techniques under different reaction conditions still require further validation. For example, in fuel cells using platinum-based catalysts, while performance in laboratory settings is promising, long-term use leads to a gradual decline in catalyst activity, directly impacting the efficiency and lifespan of fuel cells. Improving the resistance of catalysts to poisoning, oxidation, and corrosion and extending their lifespan are still key research areas for the future.

Moreover, the application of green catalysts faces challenges in scaling up production. Although some catalysts perform well in small-scale experiments, achieving industrial-scale production requires addressing issues such as material processability, production costs, and environmental impact. For instance, magnetic catalysts, despite their unique recyclability and efficiency being well-recognized in laboratory research, face aggregation and cost issues that hinder their industrial-scale application. Therefore, future research should focus not only on the laboratory performance of catalysts but also on their feasibility and economic viability in actual industrial production. To overcome these challenges, future research directions should focus on the following areas: first, further exploration of new green catalyst design and synthesis methods to enhance their activity, selectivity, and stability while reducing production costs. For example, through molecular design and materials engineering, more efficient and environmentally friendly catalysts can be developed. Additionally, integrating cutting-edge technologies such as artificial intelligence and machine learning can accelerate catalyst screening and optimization, thereby improving research efficiency. Secondly, future research should also focus on catalyst regeneration and recycling technologies, optimizing process design to achieve efficient catalyst recovery and reuse, thus reducing resource consumption and environmental impact. Finally, green catalysts hold broad application prospects in

emerging fields, particularly in carbon capture and utilization, renewable energy conversion, and environmental remediation.

As global attention to sustainable development increases, the application of green catalysts in these fields will further drive the green transformation and low-carbon development of the chemical industry. Therefore, future research should not only address current challenges but also actively explore new application scenarios and technological breakthroughs to achieve widespread use of green catalysts in more fields.

6. Conclusion

Green catalysts, as a key technology driving the sustainable development of the chemical industry, have already demonstrated significant application potential in various fields. This paper analyzes different types of green catalysts and their applications in chemical reactions, elucidating their unique advantages in improving reaction efficiency, reducing energy consumption, and minimizing by-product generation. Additionally, the paper discusses the design and synthesis of green catalysts, optimization of reaction conditions, and technologies for catalyst recycling and regeneration, further emphasizing the critical role these factors play in enhancing catalyst performance. Despite the challenges facing the development of green catalysts, such as the complexity of synthesis processes, high material costs, and issues with stability and durability in practical applications, these challenges provide clear directions for future research. Through continuous innovation and technological progress, particularly in the development of new catalyst materials, process optimization, and large-scale production, green catalysts are expected to gain broader industrial applications and play a greater role in environmental protection and resource conservation.

As global attention to sustainable development deepens, green catalysts will exhibit even broader application prospects in emerging fields such as carbon capture and utilization, renewable energy conversion, and environmental remediation. To achieve this goal, researchers must continue to explore new catalyst materials and technological breakthroughs, optimize existing processes, and transition green catalyst applications from the laboratory to industrial practice. Through such efforts, green catalysts will provide strong support for the green transformation and low-carbon development of the global chemical industry. In summary, the development of green catalysts represents not only a major transformation in the chemical industry but also an important pathway to achieving global sustainability goals. Future research and practice, driven by green catalysts, will bring cleaner and more efficient production methods to human society, ultimately achieving a win-win situation for both the economy and the environment.

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