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Green Catalysis in Environmental Remediation: A Comprehensive Review of Current Trends

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Abstract
The rapid industrialization and expansion of human activity have contributed to severe environmental contamination, including the accumulation of toxic pollutants in water, air, and soil. Conventional remediation strategies, while effective to some extent, often entail energy-intensive procedures and generate secondary waste. An effective, sustainable, and environmentally responsible method for tackling these issues is green catalysis, which is based on the ideas of green chemistry. This review covers photocatalysis, heterogeneous catalysis, nanocatalysis, and biocatalysis and provides an overview of current developments in green catalysis for environmental remediation. This review includes sustainable synthesis approaches and catalyst design strategies. The challenges of high cost, catalyst deactivation, and scalability are highlighted alongside future perspectives such as AI-driven catalyst optimization, solar-driven catalysis, and integration with circular economy concepts.

Keywords: Green catalysis, environmental remediation, photocatalysis, nanocatalysis, biocatalysis, sustainable chemistry

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Introduction

Environmental pollution is one of the defining challenges of the 21st century. The release of persistent organic pollutants (POPs), dyes, heavy metals, pharmaceuticals, agrochemicals, and greenhouse gases into the environment has resulted in ecological imbalance and health hazards [1]. Traditional approaches to remediation including adsorption, chemical precipitation, and incineration have limitations such as high operational costs, secondary waste generation, and incomplete degradation.

In this context, green catalysis has emerged as a powerful approach to environmental remediation. It leverages the use of efficient, reusable, and non-toxic catalysts that operate under mild conditions and minimize harmful by-products. According to the 12 principles of green chemistry, catalysts should enhance reaction selectivity, reduce energy consumption, and promote atom economy [2]. Green catalysis encompasses several techniques, such as photocatalysis, nano-catalysis, heterogeneous catalysis, and bio-catalysis, which have shown promising applications in treating industrial effluents [3].

The primary goal of this review is to provide a comprehensive and critical overview of the role of green catalysis in environmental remediation. While numerous studies have demonstrated the effectiveness of catalysts for pollution control, there is still a need to consolidate the scattered literature into a structured framework that highlights the current progress, limitations, and future directions. The specific objectives of this review are as follows:

- To Define and Contextualize Green Catalysis
- To Summarize Current Methodologies in Green Catalysis
- To Review Current Trends and Applications
- To Critically Assess the Challenges
- To Outline Future Perspectives
- To Serve as a Reference Framework

Methodologies in Green Catalysis

Photocatalysis

Photocatalysis is among the most widely studied catalytic approaches for environmental remediation.

Mechanism: Photocatalysis relies on semiconductors (e.g., TiO_2, ZnO, g-C_3N_4, WO_3). When exposed to light energy greater than their band gap, electrons (e^-) are excited from the valence band (VB) to the conduction band (CB), leaving behind holes (h^+). These charge carriers initiate redox reactions:

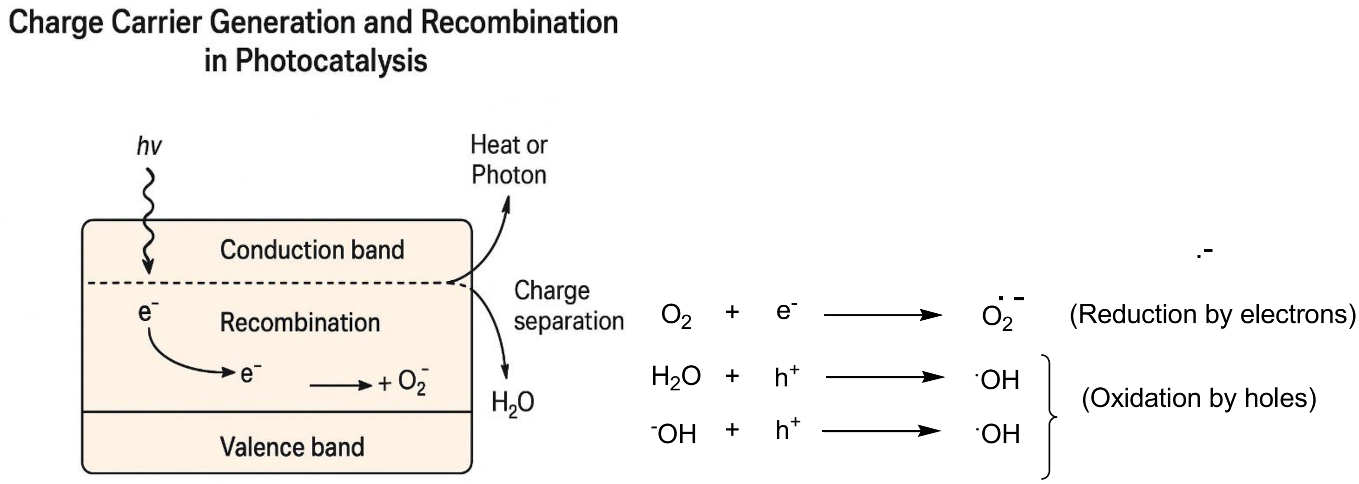

Figure 1 Charge Carrier Dynamics in Photocatalysis

The radicals degrade dyes, pesticides, and pharmaceuticals into CO_2, H_2O, and less toxic species [3]. Recent Advances include doping strategies (Ag, Cu, Fe, N, C, and S), heterojunction catalysts like TiO_2/g-C_3N_4 composites and plasmonic photocatalysis using noble metals such as Au and Ag [4]. Applications are found in textile wastewater, pharmaceutical effluents, pesticide-contaminated water, and VOC removal.

Bio-catalysis

Bio-catalysis involves the use of enzymes and microorganisms to transform pollutants under mild, eco-friendly conditions. Enzymes such as laccases, peroxidases, and dehalogenases oxidize or hydrolyze organic pollutants, while microorganisms metabolize hydrocarbons, pesticides, and phenolic compounds into less toxic forms [15].

The enzyme's active site is a three-dimensional pocket whose shape, size, and lining residues determine which substrates can bind, how they are oriented, and whether the transition state can be stabilized. Enzymes accelerate reactions primarily by stabilizing the transition state through precisely positioned polar or charged residues, hydrogen bonding, and in some cases metal ions or organic cofactors.

However, limitations in biocatalysis arise if the substrate does not fit properly, if the enzyme cannot effectively stabilize the transition state, or if the product binds too tightly, slowing turnover. These factors make the active site the primary determinant of catalytic efficiency. Strategies to enhance enzyme performance include immobilization techniques and genetic engineering to develop recombinant strains with improved activity and stability. Applications of biocatalysis are diverse, including enzyme-mediated remediation of dyes and endocrine-disrupting compounds, microbial consortia for oil spill cleanup, and biosorption of heavy metals, demonstrating its potential as a sustainable and versatile tool for environmental remediation.

Nano catalysis

Nano catalysis exploits nanoparticle's high surface area, unique morphology, and tunable electronic properties [16].

Mechanism: Nano catalysts accelerate redox and adsorption processes by providing reactive sites and enhancing electron transfer.

Key Nano catalysts include nano zero-valent iron (nZVI) for reducing chlorinated organics and heavy metals [17], magnetic nanoparticles for easy separation, noble metal nanoparticles (Pd, Pt, Au) with high catalytic activity, and carbon-based nanomaterials like graphene and CNTs [18]. Applications include groundwater remediation, catalytic ozonation, and advanced oxidation, though challenges remain with nanotoxicity and large-scale recovery.

Heterogeneous Catalysis

Heterogeneous catalysis involves catalysts in the solid phase interacting with pollutants in the liquid or gas phase. The basic mechanism involves adsorption of pollutants on the catalyst surface, subsequent chemical transformation, and release of products, while the catalyst itself remains chemically unchanged.

Table 1 Comparative Analysis of Doped Photocatalytic Systems

System	Reported efficiency	Light source	Main advantages	Common drawbacks
Ag-doped / Ag-loaded TiO_2	~80–96% dye (MB/RhB) photodegradation in 30–90 min; enhanced visible response vs. bare TiO_2 but mineralization often incomplete [5].	Visible/ solar	Extends absorption into visible via plasmonic/SPR and improves e^-/h^+ separation; antibacterial effects.	High cost, risk of silver leaching and incomplete pollutant removal.
Cu-doped TiO_2	70–99% dye or pollutant removal reported based on Cu loading and porosity [6].	Visible light/ solar	Strong visible absorption, low-cost metal dopant; can show antibacterial effects.	Thermal instability of some Cu states, recombination centers at high loading, potential Cu leaching and toxicity.
Fe-doped TiO_2	Moderate visible activity; examples report 60–90% dye removal with optimized Fe%. Band gap redshift reported (e.g., to ~2.7–3.0 eV) [7, 8].	Visible/ sunlight	Cheap, earth-abundant dopant; broad absorption shift and increased redox sites.	Excess Fe causes recombination centers, possible Fenton-like side reactions, and stability issues in long runs.
N-doped (nonmetal)/C or N-doped carbon–TiO_2 composites	Large improvements in visible-light dye degradation (often 70–95% in lab tests); enhanced adsorption and charge transfer [9].	Visible/ solar	Narrowed band gap, improved visible absorption, increased surface area and adsorption (especially with porous N-C), and good electron conductivity when carbon present.	Excess carbon can block TiO_2 sites, N-doping reproducibility and thermal stability vary and leading to inconsistent performance.
S-doped TiO_2 (and other nonmetals)	Reported visible activity improvements; sometimes 50–85% dye removal under visible light with optimized S content [10].	Visible/ solar	Band gap narrowing via anion states, often inexpensive.	Formation of mid-gap states that act as recombination centers if overdosed and control of doping chemistry is challenging.
TiO_2 / g-C_3N_4 heterojunction	Frequently >90% dye degradation in 30–120 min in optimized systems; good visible-light performance and higher mineralization than single components [11, 12].	Visible/ solar	Strongly improved charge separation complementary band positions, low cost for g-C_3N_4.	Interfacial contact and intimate coupling required; stability under long illumination and sometimes incomplete mineralization without co-catalyst.
Plasmonic photocatalysis (Au/Ag nanoparticles on TiO_2)	Reported boosts of several-fold in photodegradation rates depending on NP morphology; strong visible activity [13, 14].	Visible/ solar	Strong light harvesting via localized surface plasmon resonance (LSPR); hot-electron injection can drive reactions under visible light.	Noble metal cost, potential aggregation under reaction conditions, possible metal leaching, and complexity of optimizing NP size.

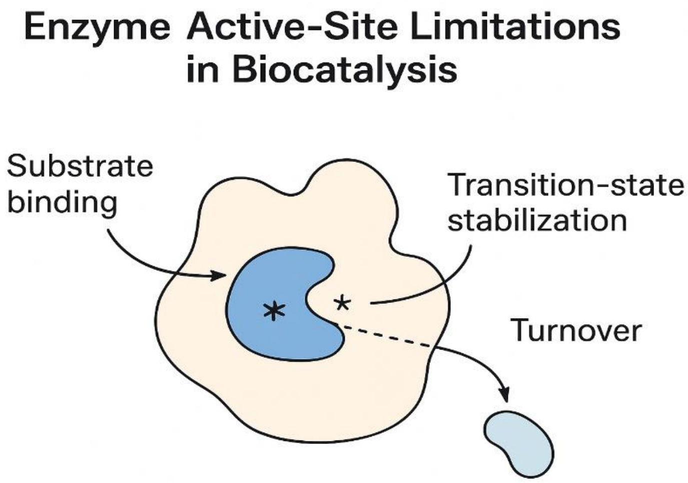

Figure 2 Enzyme Active - Site Mechanism

Common catalysts include zeolites for ion-exchange and adsorption, perovskites (ABO_3 structures) for VOC and NOx oxidation [19], metal-organic frameworks (MOFs) with high porosity and supported catalysts such as transition metals on silica or biochar. Applications include wastewater treatment, gas-phase catalytic oxidation, and catalytic ozonation.

Heterogeneous catalysts may experience surface fouling, mass transfer limitations, and leaching of active metals, all of which can reduce long-term efficiency, and their performance is also strongly influenced by reaction conditions such as temperature, P^H, and light exposure.

Comparison of catalytic approaches

Catalytic approaches such as photocatalysis, nanocatalysis, biocatalysis, and heterogeneous catalysis have emerged as promising tools for sustainable environmental remediation, each with distinct advantages and challenges. Photocatalysis utilizes solar energy to degrade pollutants under mild conditions, offering a green and efficient pathway for detoxification. However, its large-scale application is limited by poor visible-light utilization, charge carrier recombination, and dependence on UV irradiation [20, 21]. Nanocatalysis enhances reactivity and selectivity through high surface-to-volume ratios and quantum effects, yet concerns about nanoparticle toxicity, metal leaching, and synthesis costs persist [22, 23]. Biocatalysis, employing enzymes or microorganisms, provides high specificity and operates under mild, eco-friendly conditions; however challenges such as enzyme instability, P^H, temperature sensitivity, and limited reusability constrain its industrial application [24, 25]. Heterogeneous catalysis, in contrast, offers easy recovery, reusability, and scalability but often suffers from low selectivity, catalyst deactivation, and higher activation energy requirements [26, 27]. Overall, integrating the strengths of these catalytic systems through hybrid or synergistic approaches could pave the way for more efficient, sustainable, and economically viable solutions for environmental remediation.

To assess the environmental and economic viability of these catalytic systems, recent life cycle assessment (LCA) and techno-economic analysis (TEA) studies have provided valuable insights. For photocatalysis [28, 29], studies have demonstrated that although TiO_2-based systems show excellent degradation potential, energy consumption during synthesis and UV dependency increase their carbon footprint [30], while immobilized TiO_2 configurations are advantageous for scalable water purification. Nanocatalytic systems have been analyzed [31] using LCA and TEA approaches, showing that recyclable and green nanomaterials can significantly lower environmental impacts and improve process economics. Biocatalytic pathways exhibit substantial sustainability advantages [32], as enzymatic synthesis routes can outperform conventional chemical processes in terms of global warming potential [33], and renewable feedstocks in biocatalytic conversions further enhance environmental performance. In heterogeneous catalysis [34, 35], techno-economic analyses have shown that while these systems are economically promising for CO_2 conversion and renewable energy production, improvements in catalyst longevity and energy input are essential for industrial viability. Collectively, these findings reveal that integrating LCA and TEA into catalyst design and process optimization is crucial for advancing sustainable catalytic technologies. The summery of reported LCA and TEA studies are given in the **Table 2**.

Table 2 Compilation of reported LCA and TEA findings

S.No.	Catalytic System	Assessment Type	Functional Unit / Scope	Key Findings
1	TiO_2 and graphene oxide–TiO_2 nanocomposites for solar photocatalytic degradation [36].	LCA	Comparative cradle-to-gate LCA for catalyst synthesis and operation	Graphene oxide modification improves photocatalytic efficiency but increases production impacts; material synthesis dominates environmental burden.
2	Immobilized vs. slurry TiO_2 photocatalytic reactors [37].	LCA	Full life-cycle assessment from material preparation to operation	Immobilized systems reduce catalyst loss but increase material and energy inputs; optimal configuration depends on scale and reuse cycles.
3	Hybrid photochemical and biological processes for effluent treatment [38].	TEA	Process-scale assessment including capital and O&M costs	Integration with biological stages improves economic feasibility; main cost drivers are reactor size, light energy source, and catalyst lifespan.
4	Magnetite-based photocatalysts for sustainable water treatment [39].	Review (LCA + TEA)	Discussion of TEA–LCA integration in green photocatalysis	Highlights the need for coupling LCA and TEA early in catalyst design to guide scalable and cost-effective green remediation technologies.

Review of Current Trends in Green Catalysis

Green catalysis for environmental remediation has rapidly advanced in recent years, with research focusing on sustainable synthesis methods, hybrid catalytic systems, and integration with renewable energy. The following subsections summarize major emerging trends:

Green Synthesis of Catalysts

Conventional catalyst synthesis often requires toxic reducing agents, organic solvents, and energy-intensive methods. Recent studies have emphasized green synthesis routes:

- Plant-mediated synthesis: Extracts from neem, tea, Aloe vera, and citrus fruits act as reducing and capping agents for nanoparticles.
- Microbial-assisted synthesis: Bacteria, fungi, and algae reduce metal ions into nanoparticles with controlled size and morphology.
- Biopolymer supports: Natural polymers like chitosan, cellulose, and starch stabilize nanoparticles and enhance catalytic activity [40].
- Benefits: Eco-friendliness, low cost, scalability using agricultural or food waste. Ex: Silver nanoparticles synthesized using tea polyphenols for dye degradation in wastewater [41].

Biochar-Supported Catalysts

Biochar, derived from pyrolyzed biomass, has emerged as a sustainable support material for catalysts.

- Advantages: Large surface area, porosity, functional groups for binding active metals, and carbon-rich structure for electron transfer.
- Applications include Fe–biochar composites for Fenton-like oxidation of dyes [42] and MnO_2–biochar for heavy metal adsorption and catalysis [43].
- Circular Economy Link: Utilization of agricultural residues (rice husk, coconut shells, sugarcane bagasse) for catalyst production minimizes waste [44].

Hybrid and Synergistic Catalytic Systems

Single catalytic systems often face limitations such as recombination of charge carriers in photocatalysis or fouling in adsorption. Hybrid systems combine multiple approaches for synergistic effects:

- Photocatalysis + Adsorption: Adsorbents like activated carbon or MOFs capture pollutants near catalyst surfaces, enhancing degradation rates.
- Photocatalysis + Membrane Filtration: Integrated systems achieve simultaneous pollutant removal and water purification.
- Biocatalysis + Nanocatalysis: Microorganisms degrade complex pollutants, while nanoparticles accelerate breakdown of recalcitrant compounds.
- Example: TiO_2/graphene composites showing higher photocatalytic degradation efficiency for antibiotics in water [45].

Carbon Dioxide Utilization and Greenhouse Gas Mitigation

Green catalysis is increasingly applied not just for pollutant degradation, but also for valorisation of greenhouse gases.

- Catalytic CO_2 reduction: Conversion of CO_2 into methanol, formic acid, methane, and other value-added chemicals [46].
- Photocatalytic CO_2 fixation: Semiconductor-based catalysts drive CO_2 reduction under solar light.
- Methane activation: Catalytic partial oxidation of CH_4 into syngas or methanol for industrial use.
- Impact: Simultaneously addresses climate change mitigation and resource recovery.

Plasmonic and Visible-Light Catalysts

Traditional photocatalysts like TiO_2 require UV light, which accounts for only 4–5% of solar energy. Recent research emphasizes visible-light-driven catalysis:

- Plasmonic photocatalysts: Noble metals (Au, Ag) generate localized surface plasmon resonance (LSPR), enhancing light absorption.
- Band-gap engineering: Non-metal doping (N, C, and S) or heterojunction formation extends the light absorption range.
- Applications: Solar-driven wastewater treatment, indoor air purification.
- Example: Ag-doped g-C_3N_4 exhibiting enhanced photocatalytic degradation of tetracycline under visible light [47].

Circular Economy Integration

Green catalysis is strongly aligned with circular economy principles, emphasizing waste-to-resource strategies.

- Industrial by-products as precursors: Fly ash, red mud, and steel slag are used as supports or active catalysts [48].
- Biomass valorization: Waste biomass converted into carbon materials for catalytic applications [49].
- Closed-loop systems: Combining remediation with energy or resource recovery.
- Example: Converting waste plastics into carbon-based catalysts for Fenton-like oxidation of pollutants [50].

Smart and Responsive Catalysts

The new generation of catalysts is being designed with intelligent properties:

- P^H-responsive catalysts: Activate only under acidic/basic conditions, preventing unnecessary reactions.
- Self-healing catalysts: Repair structural damage during operation.
- Magnetically recoverable catalysts: Facilitate easy separation and reuse after wastewater treatment [51].

Digital and AI-Assisted Catalyst Design

Computational modelling, artificial intelligence (AI), and machine learning (ML) are revolutionizing catalyst discovery.

- Machine learning models: Predict catalyst efficiency, stability, and pollutant degradation pathways [52].
- High-throughput simulations: Rapid screening of potential catalysts without trial-and-error experiments [53].

- Data-driven optimization: Use of big data to correlate structure–activity relationships.

Challenges in Green Catalysis

Despite significant progress, scaling green catalysis from lab to industrial use faces scientific, technical, economic, and environmental challenges [54].

Scalability and Industrial Implementation

Most studies remain at lab scale under ideal conditions. Producing catalysts with consistent quality and integrating them into existing plants is difficult [55].

High Cost of Catalyst Materials

Noble metals (Pd, Pt, Au, Ru) and rare earths (Ce, La) are costly and scarce. Alternatives like Fe, Cu, Mn, and Ni show lower efficiency. Recovery and recycling are not always effective [56].

Catalyst Deactivation and Stability

Catalysts may lose activity via fouling, poisoning, or structural degradation. Photocatalysts face charge recombination, while biocatalysts are sensitive to pH, temperature, and co-contaminants [57].

Environmental and Health Risks of Nanocatalysts

Nanoparticles (Ag, TiO_2, nZVI) may pose risks such as bioaccumulation and ecotoxicity. Safe disposal and handling protocols are still emerging.

Energy and Process Efficiency

Some systems (UV photocatalysis, catalytic ozonation) require high energy input, limiting sustainability. Shifting toward solar-driven or ambient processes is challenging [58].

Complexity of Real Waste Streams

Industrial effluents are complex, unlike single-pollutant lab tests. Pollutant interactions and conditions such as high salinity reduce performance.

Limited LCA and Techno-Economic Studies

Most studies focus on degradation efficiency, with little attention to life-cycle impacts or cost feasibility, leading to incomplete claims of “green” status.

Regulatory and Policy Barriers

Lack of guidelines, safety standards, and incentives hinders adoption. Variations in international policies create uncertainty in commercialization.

Future Perspectives

Green catalysis offers transformative potential for environmental remediation; however, its large-scale realization hinges on overcoming key challenges related to cost, safety, and scalability**.** Among these, the high synthesis cost and limited availability of noble metals remain the most urgent issues, calling for the development of low-cost, earth-abundant catalysts (e.g., Fe, Cu, Ni, Mn) supported on natural clays, biochar, or industrial waste-derived materials. Such approaches can significantly reduce material costs while promoting circular economy practices. Safety and toxicity associated with nanomaterials and metal leaching must also be addressed through the design of stable, recyclable, and non-toxic catalysts, possibly encapsulated or surface-modified for minimal environmental release.

To tackle scalability and performance consistency, future work should emphasize AI-driven catalyst design and machine learning-based predictive modelling, enabling rapid screening of composition–activity relationships and optimization of synthesis parameters. Integration with renewable energy systems, especially solar-driven photocatalysis and solar-assisted advanced oxidation processes, will further improve energy efficiency and sustainability. Moreover, hybrid catalytic systems combining biocatalytic, photocatalytic, and nano-catalytic mechanisms can enhance degradation efficiency and selectivity for persistent and emerging contaminants such as pharmaceuticals, micro/nanoplastics, and antibiotic-resistant bacteria.

A critical research direction involves industrial waste valorization, where catalytic systems convert waste streams into valuable products, achieving dual benefits of remediation and resource recovery. Furthermore, incorporating Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) into catalyst development pipelines will help evaluate real-world feasibility and guide industrial adoption. Moving forward, establishing regulatory guidelines for nanocatalyst handling and fostering interdisciplinary collaboration across chemistry, engineering, data science, industry, and policy along with global partnerships, will be essential to achieve large-scale sustainable adoption.

Conclusion

Green catalysis has emerged as a transformative approach to environmental remediation, offering sustainable, energy-efficient and eco-friendly alternatives to conventional pollutant removal technologies. By leveraging heterogeneous, photocatalytic, nano-catalytic, and biocatalytic systems, researchers have demonstrated significant advances in the degradation of organic pollutants, detoxification of heavy metals, removal of emerging contaminants and restoration of environmental quality. This review highlights that while substantial progress has been achieved, real-world implementation remains a challenge. Catalyst deactivation, high costs of noble metals, scalability issues, and the risks associated with nano-catalyst release continue to hinder widespread adoption. Moreover, most laboratory studies are conducted under idealized conditions, whereas actual industrial effluents are complex mixtures that require robust and adaptable catalytic systems. Nevertheless, the future outlook is highly promising**.** Emerging strategies such as waste-derived catalysts, bio-inspired synthesis, solar-driven photocatalysis, multifunctional smart catalysts and AI-guided catalyst design are expected to accelerate progress. Embedding life-cycle and techno-economic assessments into research and design frameworks will ensure environmental and economic viability. By addressing current challenges through interdisciplinary collaboration and innovation, the transition from laboratory breakthroughs to field-scale applications can be realized. This review thus provides a consolidated framework for understanding past progress, present limitations, and future opportunities in the field of green catalysis, serving as a foundation for researchers, industry, and policymakers committed to building a cleaner and more sustainable future.

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