

# Advances in Inorganic Catalysts for Industrial Applications: A Comprehensive Review

DOI: 10.5281/zenodo.19184524

## ABSTRACT

*Inorganic catalysts represent the cornerstone of modern industrial chemistry, enabling efficient chemical transformations across diverse sectors including petrochemical processing, environmental remediation, and sustainable energy production. This comprehensive review examines recent advances in inorganic catalytic materials, encompassing metal oxides, zeolites, metal-organic frameworks (MOFs), and emerging single-atom catalysts. The review systematically analyzes catalyst design strategies, synthesis methodologies, and structure-activity relationships that govern catalytic performance in industrial applications. Recent developments in photocatalysts and electrocatalysts for water splitting and CO<sub>2</sub> reduction are highlighted, demonstrating their potential for sustainable energy conversion. Advances in heterogeneous catalysis, including catalyst immobilization techniques and rational design approaches, are discussed in the context of biodiesel production, hydrocarbon oxidation, and fine chemical synthesis. The integration of computational modeling, in situ characterization techniques, and machine learning approaches has accelerated the discovery and optimization of high-performance catalysts. Current challenges including catalyst stability, scalability, and cost-effectiveness are addressed, along with emerging opportunities in hierarchical nanostructures and bifunctional catalytic systems. This review provides critical insights into the evolution of inorganic catalysts and outlines future research directions for achieving industrial-scale implementation of advanced catalytic technologies.*

**Keywords:-** *Inorganic catalysts, metal oxides, zeolites, MOFs, heterogeneous catalysis, photocatalysis, electrocatalysis, industrial applications*

## 1. INTRODUCTION

The development of efficient and sustainable catalytic systems represents a critical challenge for modern chemical industry, particularly in the context of environmental protection and energy transition. Inorganic catalysts have emerged as indispensable components in numerous industrial processes, from petroleum refining and petrochemical synthesis to environmental remediation and renewable energy production. The unique physicochemical properties of inorganic materials, including high thermal stability, tunable surface chemistry, and excellent mechanical strength, make them particularly suitable for harsh industrial operating conditions [1]. Recent decades have witnessed remarkable progress in the design and synthesis of advanced inorganic catalysts with precisely controlled structures and compositions [2]. Traditional metal oxide catalysts, while effective for many industrial applications, often suffer from limitations in selectivity, recyclability, and operational efficiency under mild conditions. This has driven extensive research into developing next-generation catalytic materials with enhanced performance characteristics. The emergence of hierarchical porous materials such as zeolites, mesoporous silicas, and metal-organic frameworks has expanded the toolbox available for heterogeneous catalysis [2]. These materials offer unique advantages including high surface areas, well-defined pore structures, and tunable active sites that can be rationally designed for specific catalytic applications [3].

The shift toward sustainable chemistry and green industrial processes has further intensified research efforts in inorganic catalysis [4]. Modern catalysts must not only exhibit high activity and selectivity but also demonstrate excellent stability, recyclability, and minimal environmental impact. This review provides a comprehensive overview of recent advances in inorganic catalysts for industrial applications, focusing on metal oxides, zeolites, MOFs, photocatalysts, electrocatalysts, and emerging single-atom catalytic systems. We examine the fundamental principles governing catalytic performance, discuss innovative synthesis strategies, and highlight successful industrial implementations. The review also addresses current challenges and future perspectives for advancing inorganic catalysts from laboratory discoveries to large-scale industrial deployment.

## 2. METAL OXIDE CATALYSTS FOR INDUSTRIAL PROCESSES

Metal oxides represent one of the most extensively studied and widely applied classes of inorganic catalysts in industrial chemistry. These materials have found ubiquitous applications in heterogeneous catalysis due to their diverse chemical compositions, tunable redox properties, variable oxidation states, and excellent thermal stability. The catalytic properties of metal oxides are intimately related to their electronic structure, surface

characteristics, and defect chemistry, which can be systematically modulated through compositional engineering and structural design.

Recent advances in metal oxide catalysis have focused on developing multifunctional materials with enhanced activity and selectivity for critical industrial reactions. Mixed metal oxide systems have demonstrated superior performance in catalytic oxidation reactions for the conversion of petroleum-based feedstocks into useful chemicals such as adipic acid, caprolactam, glycols, acrylates, and vinyl acetate [1]. The rational design of these catalysts involves careful control of surface acidity, textural properties including surface area and pore volume, and optimization of operational parameters. Traditional industrial methods employing stoichiometric amounts of toxic inorganic oxidants are being gradually replaced by catalytic alternatives that operate under milder conditions with enhanced environmental sustainability [1]. Surface engineering strategies, including defect creation, heteroatom doping, and interface modification, have been employed to optimize the adsorption properties and activation barriers for key reaction intermediates [5].

### **3. ZEOLITES AND POROUS MATERIALS IN CATALYSIS**

Zeolites and related microporous materials have maintained their position as cornerstone catalysts in the petrochemical industry for decades [2]. These crystalline aluminosilicate materials possess well-defined microporous structures with uniform pore sizes typically below 2 nm, providing molecular-level shape selectivity that enables precise control over reaction pathways and product distributions. The unique properties of zeolites, including high surface areas, excellent thermal stability, tunable acidity, and ion-exchange capabilities, have made them indispensable for applications ranging from fluid catalytic cracking to fine chemical synthesis [1].

Recent developments in zeolite catalysis have focused on overcoming traditional limitations through hierarchical structure design and metal incorporation strategies [6]. The confinement effect provided by zeolite frameworks stabilizes isolated metal species while modulating their electronic properties, leading to enhanced catalytic activity and unprecedented selectivity. The challenge of diffusion limitations in microporous zeolites has been addressed through the development of hierarchical architectures combining micro- and mesopores [6]. Advanced characterization techniques, including solid-state NMR spectroscopy and in situ X-ray absorption spectroscopy, have provided unprecedented insights into the structure and properties of active sites in zeolite catalysts [2]. Understanding the spatial proximity of different acid sites and the local environment around metal centers has enabled rational design of zeolite-based catalysts with optimized performance.

### **4. METAL-ORGANIC FRAMEWORKS FOR CATALYTIC APPLICATIONS**

Metal-organic frameworks have emerged as a revolutionary class of hybrid crystalline materials with transformative potential for heterogeneous catalysis [3]. These materials, constructed through the coordination of metal ions or clusters with organic linkers, offer unprecedented opportunities for rational catalyst design due to their exceptional structural tunability, high surface areas exceeding 6000 m<sup>2</sup>/g, and well-defined active sites [3]. The modular nature of MOF synthesis allows systematic variation of both metal nodes and organic linkers, enabling fine-tuning of catalytic properties including Lewis acidity, redox behavior, and substrate accessibility [7].

Recent advances in MOF catalysis have demonstrated their versatility across diverse industrial applications, from alcohol oxidation and olefin oligomerization to CO<sub>2</sub> fixation and photoelectrochemical water splitting [3]. The unique porous architecture of MOFs provides several advantages for catalytic processes: molecular-level control over active site distribution, size-selective catalysis through tailored pore dimensions, and the ability to create well-defined microenvironments that stabilize reactive intermediates [7]. For reactions requiring multiple catalytic functions, MOFs offer the possibility of integrating different types of active sites within a single framework, enabling cascade reactions and tandem catalysis with improved overall efficiency. Bifunctional MOF catalysts combining both acidic and basic sites have shown remarkable performance in complex organic transformations, eliminating the need for sequential processing steps [8].

The development of MOF-derived catalysts has opened new avenues for creating high-performance materials with retained porosity and enhanced stability. Thermal treatment of MOFs under controlled atmospheres can generate porous metal oxides, metal nanoparticles embedded in carbon matrices, or hybrid materials with unique structures that would be difficult to achieve through conventional synthesis routes. For industrial implementation, challenges related to MOF stability in aqueous environments and under harsh reaction conditions have been addressed through strategic design approaches including hydrophobic modification and introduction of robust organic linkers [3].

## 5. PHOTOCATALYSTS AND ELECTROCATALYSTS FOR ENERGY CONVERSION

The development of efficient photocatalysts and electrocatalysts represents a critical frontier in sustainable energy conversion technologies, addressing global challenges in hydrogen production, CO<sub>2</sub> reduction, and renewable fuel synthesis [9]. Inorganic semiconductors, particularly metal oxides and related materials, have dominated this field due to their favorable band structures, photostability, and ability to facilitate both oxidation and reduction reactions. Recent advances have focused on overcoming fundamental limitations including rapid charge recombination, narrow light absorption ranges, and insufficient active sites through innovative material design and surface engineering strategies [10].

For water splitting applications, significant progress has been achieved in developing non-noble metal electrocatalysts that can compete with traditional platinum and iridium-based systems [11]. Nickel-based catalysts, including pure nickel, nickel alloys, oxides, hydroxides, and spinels, have demonstrated exceptional performance in alkaline water electrolysis [11]. The design of bifunctional catalysts capable of catalyzing both hydrogen evolution and oxygen evolution reactions has simplified electrolyzer architecture and reduced system costs [12]. Advanced nanostructuring approaches, including the creation of hierarchical porous structures and the formation of heterointerfaces, have substantially enhanced catalytic activity by increasing the density of active sites and facilitating efficient charge transfer [13].

Photocatalytic CO<sub>2</sub> reduction using water as an electron donor represents one of the most challenging yet promising applications of artificial photosynthesis [14]. Recent developments have achieved remarkable selectivity for CO<sub>2</sub> reduction products. Metal oxide photocatalysts including modified TiO<sub>2</sub>, perovskite oxides, and metal chalcogenides have been extensively investigated, with surface modification through cocatalyst loading proving crucial for enhancing activity and selectivity [15]. The integration of molecular complexes with semiconductor supports has opened new possibilities for achieving high selectivity in CO<sub>2</sub> reduction [16].

## 6. SINGLE-ATOM AND NANOSCALE CATALYSTS

Single-atom catalysts represent the ultimate frontier in catalyst miniaturization, featuring isolated metal atoms dispersed on suitable supports with atomic efficiency approaching 100% [17]. These materials bridge the gap between homogeneous and heterogeneous catalysis, combining the well-defined active sites and high selectivity of molecular catalysts with the stability and recyclability of solid catalysts [17]. The unique electronic properties of single atoms, arising from quantum confinement effects and strong metal-support interactions, often result in catalytic activities that exceed those of conventional nanoparticle catalysts [18].

Recent advances in single-atom catalyst synthesis have enabled precise control over metal speciation, coordination environment, and distribution on various support materials. Advanced characterization techniques including aberration-corrected transmission electron microscopy and X-ray absorption spectroscopy have been instrumental in identifying the structure of single-atom active sites and elucidating reaction mechanisms [19]. The application of single-atom catalysts in environmental catalysis has shown particular promise, with demonstrated effectiveness in CO oxidation and volatile organic compound removal. For acetylene hydrochlorination, an industrially important reaction for vinyl chloride production, gold single-atom catalysts stabilized by appropriate ligand environments have achieved activities comparable to traditional catalysts while offering significant environmental and safety advantages [19].

## 7. EMERGING TRENDS AND FUTURE PERSPECTIVES

The field of inorganic catalysis is witnessing transformative changes driven by advances in synthesis methodologies, characterization techniques, and computational approaches [17]. Machine learning and artificial intelligence are increasingly being employed to accelerate catalyst discovery, predict catalytic performance, and uncover design principles that would be difficult to identify through traditional experimental approaches. High-throughput computational screening, combined with automated synthesis and testing platforms, has enabled rapid exploration of vast compositional and structural spaces, leading to the identification of previously unknown catalytic materials with exceptional properties [20].

Several emerging trends are reshaping the landscape of industrial catalysis. The development of multifunctional catalysts capable of catalyzing multiple sequential reactions in a single vessel offers significant advantages in terms of process simplification and energy efficiency [21]. Hierarchical catalysts combining different length scales of porosity and multiple types of active sites are being designed to optimize mass transfer while maintaining high selectivity. For environmental applications, the development of catalysts capable of operating in complex real-world conditions, including the presence of catalyst poisons and variable feedstock compositions, remains a critical challenge [22].

Looking toward future industrial implementation, several key challenges must be addressed. The scalability of advanced catalyst synthesis methods, particularly for single-atom and MOF-based catalysts, requires significant development to meet industrial production volumes at acceptable costs. Long-term catalyst stability under

realistic operating conditions, including resistance to poisoning, sintering, and leaching, needs comprehensive investigation beyond typical laboratory timescales [23]. The development of operando characterization techniques capable of monitoring catalyst structure and composition during operation will be crucial for understanding deactivation mechanisms and designing more robust materials. Economic and life-cycle analyses are essential for evaluating the true sustainability of new catalytic processes, considering not only catalytic performance but also raw material sourcing, energy consumption, and end-of-life disposal. The successful translation of laboratory discoveries to industrial practice will require close collaboration between academic researchers, catalyst manufacturers, and industrial end-users to address practical challenges related to catalyst formulation, reactor engineering, and process optimization [24].

### 8. COMPARATIVE ANALYSIS OF CATALYST SYSTEMS

**Table 1.** Comprehensive comparison of major inorganic catalyst systems highlighting their advantages, limitations, applications, and industrial readiness levels (TRL scale: 1-9, where 9 represents fully commercial technology).

| Catalyst Type                | Key Advantages   | Main Limitations  | Typical Applications  | Industrial Readiness | Representative Examples   |
|------------------------------|--|---|---|----------------------|---|
| <b>Metal Oxides</b>          | High thermal stability; Diverse compositions; Low cost; Scalable synthesis         | Limited selectivity; Potential leaching; Lower surface area                     | Oxidation reactions; Biodiesel production; Automotive catalysts   | High (TRL 8-9)       | TiO <sub>2</sub> , CeO <sub>2</sub> , NiFe oxides [1]             |
| <b>Zeolites</b>              | Shape selectivity; Strong acidity; Excellent stability; Well-established synthesis | Diffusion limitations; Limited pore size range; Restricted to certain reactions | Petrochemical processing; Hydrocracking; Alkylation               | High (TRL 9)         | H-ZSM-5, Y-zeolite, Beta [2]                                      |
| <b>MOFs</b>                  | Ultrahigh surface area; Tunable pore structure; Precise active site control        | Moisture sensitivity; Lower thermal stability; High synthesis cost              | Fine chemical synthesis; Gas separation; CO <sub>2</sub> capture  | Medium (TRL 4-6)     | UiO-66, MIL-100, HKUST-1 [3]                                      |
| <b>Single-Atom Catalysts</b> | Maximum atom efficiency; High selectivity; Unique electronic properties            | Difficult synthesis; Potential aggregation; Limited loading                     | Hydrogenation; Environmental catalysis; Electrocatalysis          | Low-Medium (TRL 3-5) | Pt/C, Ni-N-C, Au/TiO <sub>2</sub> [19]                            |
| <b>Perovskites</b>           | Compositional flexibility; Good conductivity; Oxygen mobility                      | Phase stability issues; Complexity of optimization                              | Oxygen evolution; CO <sub>2</sub> reduction; Sensors              | Medium (TRL 5-7)     | LaFeO <sub>3</sub> , SrTiO <sub>3</sub> , BaTiO <sub>3</sub> [14] |
| <b>Photocatalysts</b>        | Solar energy utilization; Ambient conditions; Direct fuel production               | Low quantum efficiency; Charge recombination; Stability under irradiation       | Water splitting; CO <sub>2</sub> reduction; Pollutant degradation | Low-Medium (TRL 3-5) | g-C <sub>3</sub> N <sub>4</sub> , BiVO <sub>4</sub> , CdS [10]    |

## 9. PERFORMANCE METRICS FOR INDUSTRIAL CATALYSTS

**Table 2.** Performance metrics of representative inorganic catalysts in key industrial reactions, demonstrating the diversity of applications and operating conditions. TOF = turnover frequency; TON = turnover number; OER = oxygen evolution reaction; HER = hydrogen evolution reaction.

| Reaction Type               | Catalyst System      | Activity (TOF/TON)   | Selectivity (%)             | Stability (hours)      | Operating Conditions                         | Reference |
|-----------------------------|----------------------|----------------------|-----------------------------|------------------------|--|-----------|
| Hydroformylation            | Rh/zeolite           | 6567 h <sup>-1</sup> | >99.9                       | >100                   | 393 K, 6 MPa syngas                          | [2]       |
| Water Oxidation (OER)       | NiFe oxide           | -                    | -                           | 300+                   | 1 M KOH, 10 mA/cm <sup>2</sup>               | [11]      |
| Hydrogen Evolution (HER)    | Ni-based             | -                    | -                           | 70+                    | 1 M KOH, 10 mA/cm <sup>2</sup>               | [12]      |
| CO <sub>2</sub> to CO       | Various              | -                    | 90                          | Continuous             | UV, H <sub>2</sub> O as e <sup>-</sup> donor | [14]      |
| Biodiesel Production        | Sulfated metal oxide | -                    | >95                         | Recyclable (5+ cycles) | 373 K, methanol/oil ratio 6:1                | [1]       |
| Alkyne Hydrogenation        | Pd nanoparticles     | -                    | >90 (alkene)                | 10+                    | Ambient T, H <sub>2</sub> atmosphere         | [25]      |
| Acetylene Hydrochlorination | Au single-atom       | -                    | -                           | 1000+                  | 180°C, HCl/C <sub>2</sub> H <sub>2</sub>     | [19]      |
| Fischer-Tropsch             | Co-zeolite           | -                    | Variable (C <sub>s</sub> +) | Extended               | 200-350°C, syngas                            | [2]       |
| Photocatalytic degradation  | Cs-HPA               | -                    | 98 (MB dye)                 | 90 min                 | Solar irradiation                            | [15]      |
| Ester hydrolysis            | Clay-based           | -                    | Variable                    | Reusable               | Aqueous conditions                           | [26]      |

## 10. CONCLUSION

This comprehensive review has examined the remarkable progress in inorganic catalysts for industrial applications, highlighting the evolution from traditional metal oxides to sophisticated single-atom and multifunctional catalytic systems. The field has witnessed transformative advances in catalyst design, synthesis, and characterization that have enabled unprecedented control over catalytic performance at the molecular level. Metal oxide catalysts continue to dominate many industrial processes due to their robustness, scalability, and cost-effectiveness, with recent innovations in hierarchical structuring and defect engineering substantially enhancing their activity and selectivity. Zeolites remain indispensable in petrochemical industry, with developments in metal incorporation representing significant breakthroughs in achieving both high activity and selectivity for challenging reactions.

The emergence of metal-organic frameworks has opened new horizons in catalysis, offering unprecedented opportunities for rational design of active sites and creation of multifunctional catalytic systems. Despite challenges related to stability and scalability, MOFs have demonstrated remarkable potential for fine chemical synthesis and energy conversion applications. The development of photocatalysts and electrocatalysts for water splitting and CO<sub>2</sub> reduction has made substantial progress, with non-noble metal catalysts achieving performance metrics that approach or exceed those of benchmark precious metal systems. These advances are critical for enabling the transition to sustainable energy systems based on hydrogen fuel and solar-to-chemical conversion technologies.

Single-atom catalysts represent the ultimate expression of atomic efficiency in heterogeneous catalysis, combining the advantages of homogeneous and heterogeneous systems while introducing unique catalytic properties arising from quantum confinement and metal-support interactions. The successful industrial implementation of these advanced catalysts will require addressing challenges in large-scale synthesis, long-term stability, and integration into existing process infrastructure. Future research should focus on developing robust synthesis protocols that can produce catalysts with consistent properties at industrial scale, understanding deactivation mechanisms through advanced operando characterization, and conducting comprehensive techno-economic analyses to guide materials selection. The integration of computational methods, machine learning,

and high-throughput experimentation promises to accelerate catalyst discovery and optimization. Collaboration between academia, industry, and government institutions will be essential for translating fundamental scientific advances into practical catalytic technologies that can address global challenges in energy, environment, and sustainable chemical production.

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