

Organometallic Complexes in Catalysis for Sustainable Chemistry: A Review

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Abstract

Organometallic catalysis is at the forefront of sustainable chemistry, offering highly efficient and selective solutions for critical transformations in modern chemical processes. This review comprehensively analyzes 80 studies, focusing on the use of transition metals such as palladium, nickel, and copper, which dominate reactions like hydrogenation, dehydrogenation, carbon-carbon bond formation, and carbon dioxide utilization. Additionally, the review explores the growing importance of earth-abundant metals like iron and cobalt as greener alternatives to conventional catalysts. Detailed mechanistic insights are provided into key catalytic cycles, such as oxidative addition, reductive elimination, and transmetalation, illustrating the pivotal role of ligand modifications in fine-tuning reactivity and selectivity. The potential of organometallic catalysts in CO₂ conversion is particularly highlighted, showcasing their ability to address environmental challenges by transforming CO₂ into valuable chemicals.

Despite significant advancements, challenges persist in expanding the use of cost-effective, earth-abundant metals, optimizing catalytic performance in aqueous systems, and scaling sustainable processes for industrial use. This review emphasizes the necessity of continued innovation in catalytic design, CO₂ valorization, and the integration of computational tools to predict and enhance catalytic activity. By bridging traditional and green chemistry, organometallic catalysts offer profound opportunities to revolutionize sustainable practices, with the potential to reshape industries ranging from pharmaceuticals to energy.

Keywords: Organometallic catalysis, sustainable chemistry, transition metals, CO₂ conversion, hydrogenation, earth-abundant metals, green chemistry.

INTRODUCTION

Organometallic complexes, defined by their unique structure of a metal center bound to organic ligands, have become essential in advancing catalysis for sustainable chemistry. These complexes facilitate a wide range of chemical transformations with high selectivity and efficiency, playing a crucial role in various fields such as pharmaceuticals, materials science, and environmental chemistry (1,2). Their ability to catalyze reactions under mild conditions makes them invaluable tools in developing greener and more sustainable chemical processes (3,4).

One of the most significant applications of organometallic complexes is in carbon-carbon bond formation, a fundamental reaction in organic synthesis. Transition metal catalysts, such as palladium complexes, have been instrumental in facilitating cross-coupling reactions like the Suzuki-Miyaura and Heck reactions. These processes are essential for the synthesis of biaryl compounds, which are prevalent in pharmaceuticals and agrochemicals (5,6). Moreover, these catalysts offer high functional group tolerance,

allowing for the construction of complex molecular architectures (7).

In the context of sustainable chemistry, organometallic complexes are pivotal in the activation and conversion of small molecules, such as carbon dioxide (CO₂), nitrogen (N₂), and hydrogen (H₂). The catalytic reduction of CO₂ into valuable chemicals and fuels, for instance, exemplifies how these complexes contribute to environmental sustainability. Complexes of ruthenium, cobalt, and iron have demonstrated effectiveness in these transformations, providing a route to mitigate the effects of greenhouse gases (8–10). Similarly, the catalytic reduction of N₂ to ammonia, a process crucial for fertilizer production, has been advanced through molybdenum and iron-based organometallic catalysts (11,12).

A key focus in the development of organometallic catalysts is their alignment with green chemistry principles. The chemical industry is increasingly adopting greener practices, with organometallic complexes playing a central role in this transition. These catalysts are being designed to operate in aqueous media, under ambient conditions, and with minimal waste generation, thus reducing the environmental impact of chemical processes (13,14). For instance, ruthenium and iridium complexes have been optimized for use in water, which is a non-toxic, non-flammable, and abundant solvent, making these processes more sustainable (15,16).

The versatility of organometallic complexes extends into the realm of medicinal chemistry, where they have been used in the selective modification of biomolecules. Platinum-based complexes, for instance, are widely known for their use in chemotherapy, where they induce apoptosis in cancer cells by binding to DNA. More recent advancements have focused on less toxic metals, such as gold and ruthenium, which show promise in targeting cancer cells while minimizing damage to healthy tissues (17,18). This ability to selectively modify biomolecules has profound implications for the development of new pharmaceuticals (19,20).

In addition to their chemical reactivity, organometallic complexes are increasingly being integrated with computational tools such as artificial intelligence (AI) and machine learning (ML). These technologies are revolutionizing the discovery and optimization of new catalysts by enabling the rapid screening of vast libraries of potential compounds. AI-driven models can predict catalytic activity, selectivity, and stability, significantly reducing the time and resources required for experimental testing (21,22). This approach not only accelerates the development of new catalysts but also opens up new possibilities for designing catalysts with unprecedented efficiency and selectivity (23,24).

This review aims to provide a comprehensive overview of the recent advancements in the use of organometallic complexes in catalysis, particularly focusing on their role in promoting sustainable chemistry. The discussion will cover the design and application of these complexes in various catalytic processes, emphasizing their contribution to greener chemical practices. From carbon-carbon bond formation to small molecule activation and medicinal applications, the versatility and impact of organometallic complexes in catalysis underscore their critical role in shaping the future of chemistry (2,6,13).

Literature Review

1. Fundamentals of Organic Catalysis

1.1. Basic Concepts

Organic catalysis is a fundamental aspect of modern chemistry, and organometallic catalysts, in particular, have revolutionized the way we approach chemical transformations. These catalysts, which consist of a

metal atom bonded to organic ligands, provide unique pathways for reactions that are difficult or impossible to achieve with traditional organic catalysts. The development of organometallic catalysts has allowed chemists to conduct reactions under milder conditions, with higher selectivity and greater efficiency, making them indispensable tools in both academic and industrial settings (25–27).

The role of organometallic catalysts in organic synthesis is particularly noteworthy in reactions that involve the formation of new carbon-carbon bonds. These reactions are critical for the construction of complex molecular architectures and have broad applications in pharmaceuticals, agrochemicals, and materials science (28,29). The development of catalysts that facilitate these transformations under sustainable conditions is an ongoing challenge, driving much of the current research in the field.

1.2. Common Transition Metals Used

Transition metals, such as palladium, nickel, and iron, are widely used in organometallic catalysis due to their ability to stabilize multiple oxidation states and form complexes with a variety of ligands. Palladium is particularly well-known for its role in cross-coupling reactions, such as the Suzuki-Miyaura reaction, which has become a cornerstone of modern organic synthesis (30–32). Nickel and iron, on the other hand, are gaining attention as more sustainable alternatives to palladium due to their abundance and lower toxicity (33,34). The versatility of these metals allows them to be used in a wide range of catalytic processes, from simple hydrogenation reactions to complex carbon-carbon and carbon-heteroatom bond formations (35,36).

1.3. Mechanistic Insights

The mechanisms by which organometallic catalysts operate are complex and often involve multiple steps, including oxidative addition, transmetalation, and reductive elimination. Understanding these mechanisms is crucial for the rational design of new catalysts and the optimization of existing ones. For example, in the Suzuki-Miyaura reaction, the palladium catalyst first undergoes oxidative addition with an aryl halide, followed by transmetalation with a boronic acid, and finally, reductive elimination to form the desired biaryl product (37–39). These mechanistic insights not only enhance our understanding of how these catalysts work but also provide guidelines for developing more efficient and selective catalytic systems (40,41).

2. Organometallic Catalysts in Sustainable Processes

2.1. Carbon-Carbon Bond Formation

The formation of carbon-carbon (C-C) bonds is a fundamental process in organic synthesis, and organometallic catalysts have played a pivotal role in advancing this area. Palladium-catalyzed cross-coupling reactions, such as the Heck, Suzuki, and Negishi reactions, have revolutionized the synthesis of complex organic molecules. These reactions allow for the formation of C-C bonds under mild conditions with high selectivity, making them indispensable in the synthesis of pharmaceuticals, agrochemicals, and materials (42–44). The development of nickel and iron catalysts as more sustainable alternatives to palladium is particularly noteworthy, offering greener options for these critical transformations (45,46).

2.2. Carbon-Heteroatom Bond Formation

In addition to carbon-carbon bond formation, organometallic catalysts are also crucial for the formation of carbon-heteroatom (C-X) bonds, where X is a heteroatom such as oxygen, nitrogen, or sulfur. These reactions are essential for the synthesis of various pharmaceuticals, agrochemicals, and natural products. Palladium and copper-based catalysts are particularly effective in facilitating C-X bond formation with high efficiency and selectivity. Recent advances in ligand design and catalytic systems have expanded the

scope of these reactions, enabling the synthesis of increasingly complex molecules (47–50).

2.3. Hydrogenation and Dehydrogenation Reactions

Hydrogenation and dehydrogenation reactions are vital for the production of fuels, chemicals, and pharmaceuticals. Organometallic catalysts, particularly those based on ruthenium, rhodium, and iridium, are highly active and selective in these processes. In hydrogenation, these catalysts facilitate the addition of hydrogen to unsaturated bonds, converting alkenes to alkanes or reducing ketones to alcohols. Conversely, in dehydrogenation, they remove hydrogen atoms, converting alkanes to alkenes or alcohols to ketones (51–54).

2.4. CO₂ Utilization

The catalytic conversion of carbon dioxide (CO₂) into valuable chemicals is a critical area of research in sustainable chemistry. Organometallic catalysts, particularly those based on ruthenium, cobalt, and nickel, have shown great promise in this regard. These catalysts facilitate the reduction of CO₂ to formic acid, methanol, or even hydrocarbons, providing a pathway to mitigate the effects of CO₂ emissions while generating useful products (55–58). The development of new catalytic systems that can operate under mild conditions and with high selectivity is essential for the practical application of CO₂ conversion technologies.

3. Innovations in Organometallic Chemistry

3.1. Computational Approaches to Catalyst Design

The integration of computational tools, such as density functional theory (DFT) and machine learning (ML), has revolutionized the design and optimization of organometallic catalysts. These approaches enable researchers to predict the behavior of catalysts *in silico*, allowing for the rapid screening of potential catalysts and the optimization of reaction conditions. The use of computational methods has led to the discovery of new catalysts with enhanced activity, selectivity, and stability, significantly accelerating the pace of innovation in the field (59,60).

3.1. Computational Approaches to Catalyst Design (continued)

The advancements in computational chemistry have not only accelerated the pace of discovering new catalysts but have also allowed for the detailed understanding of existing catalytic systems. This includes predicting reaction mechanisms, calculating energy profiles, and even designing novel ligands that can enhance catalyst performance (61,62). Machine learning algorithms, trained on large datasets of catalytic reactions, have begun to play a role in predicting the outcomes of catalytic processes, thus reducing the need for extensive experimental trials (63,64).

3.2. Development of New Ligands

Ligands are integral to the activity and selectivity of organometallic catalysts, as they influence the electronic and steric environment of the metal center. Recent research has focused on designing ligands that are not only more effective but also more sustainable. For instance, bio-based ligands derived from renewable resources are gaining attention for their potential to reduce the environmental footprint of catalytic processes (65,66). Additionally, the development of chiral ligands has enabled the synthesis of enantiomerically pure products, which are crucial in the pharmaceutical industry (67,68).

3.3. Sustainable Catalysis in Industry

The application of organometallic catalysts in industrial processes is crucial for advancing sustainability in chemical manufacturing. Industries are increasingly adopting these catalysts for large-scale production of chemicals, pharmaceuticals, and materials, driven by the need to reduce environmental impact and

improve efficiency. For example, the use of organometallic catalysts in the production of bulk chemicals such as ethylene and propylene has significantly reduced the energy consumption and waste generation of these processes (69,70). The development of more robust and versatile catalysts continues to enhance the sustainability of industrial processes, contributing to greener chemical practices (71,72).

3.4. Environmental Impact and Future Directions

Organometallic catalysts are poised to play an increasingly important role in addressing environmental challenges. Their ability to facilitate reactions under mild conditions and with minimal waste generation aligns with the principles of green chemistry. Future research is expected to focus on the development of catalysts that are even more selective, efficient, and sustainable. This includes the use of earth-abundant metals, the design of recyclable catalysts, and the integration of organometallic catalysis with renewable energy sources (73–76).

Results

1.1. Overview of Organometallic Catalysts

The comprehensive review of organometallic catalysts reveals that palladium, nickel, and iron are at the forefront of catalysis in sustainable chemistry. Palladium-based catalysts excel in cross-coupling reactions, with yields often surpassing 90%, making them indispensable in pharmaceutical synthesis (25,30). Nickel and iron, being more sustainable and cost-effective, are increasingly preferred for reactions such as hydrogenation and C-H activation, showing yields comparable to palladium (33).

1.2. Catalytic Efficiency and Selectivity

The efficiency and selectivity of organometallic catalysts are critical for their utility. Palladium-based catalysts are known for their high yields and selectivity in cross-coupling reactions, essential for producing complex organic molecules in high purity (20,77). Nickel and iron catalysts also demonstrate significant potential, particularly in hydrogenation and C-H activation reactions, with high efficiency and selectivity (41,65).

1.3. Environmental Impact of Catalysis

The environmental impact of organometallic catalysts has been a major focus, with nickel and iron emerging as sustainable alternatives due to their abundance and lower toxicity. These catalysts enable reactions in water, reducing the reliance on harmful organic solvents and aligning with green chemistry principles (44,58). Palladium, despite its high efficiency, is associated with higher toxicity and environmental concerns, making the shift towards nickel and iron increasingly necessary (25).

1.4. Computational Insights into Catalysis

The role of computational chemistry in optimizing organometallic catalysts is increasingly prominent. Studies using DFT and ML have provided insights into reaction mechanisms, identifying key intermediates and transition states that can enhance catalyst performance (59). These tools have been instrumental in designing catalysts with improved selectivity and efficiency, particularly for complex transformations like C-H activation and cross-coupling (55,60).

Discussion

2.1. Comparative Analysis of Catalysts

The comparison of palladium, nickel, and iron catalysts reveals distinct trade-offs between cost, efficiency, and sustainability. Palladium, while highly efficient in cross-coupling reactions, is expensive and less sustainable due to its scarcity and higher toxicity. Nickel and iron offer significant environmental and

economic benefits, with catalytic performance that rivals palladium in many reactions, particularly when used in green solvents like water (45,57).

2.2. Role of Ligands in Enhancing Catalysis

Ligand design is critical in enhancing the performance of organometallic catalysts. Bidentate ligands, for instance, have been shown to significantly increase the activity of nickel-based catalysts in cross-coupling reactions, while phosphine-based ligands stabilize palladium complexes, ensuring high yields in Suzuki-Miyaura reactions (37,63). In asymmetric catalysis, chiral ligands have proven essential in promoting enantioselectivity, enabling the synthesis of enantiomerically pure compounds crucial in pharmaceuticals (49).

2.3. Sustainability and Green Chemistry

The trend towards sustainability is evident in the increased use of nickel and iron catalysts, which are less toxic and more abundant than palladium. These catalysts, particularly when used in aqueous media, align with the principles of green chemistry by reducing the need for hazardous solvents and lowering the overall environmental impact (59,66). Iron catalysts, in particular, have demonstrated high efficiency in C-H activation and hydrogenation reactions in water, making them viable alternatives to traditional palladium-based systems (27).

2.4. Key Findings and Future Directions

Key insights from the analysis of 114 papers include:

- **Palladium Catalysts:** While palladium remains highly effective for cross-coupling reactions, its environmental impact and high cost necessitate more sustainable alternatives (23,48).
- **Nickel and Iron Catalysts:** These metals are emerging as important players in sustainable catalysis, particularly in reactions performed in green solvents (57,61).
- **Ligand Innovation:** Novel ligands, especially chiral ligands, are crucial for enhancing catalyst selectivity and efficiency (44).
- **Computational Tools:** The use of computational methods like DFT and ML is increasingly critical for optimizing catalyst design and improving reaction outcomes (78).

Future research should focus on further optimizing these catalysts and exploring earth-abundant metals like cobalt and copper, along with bio-based ligands and renewable feedstocks, to achieve fully sustainable chemical processes (79,80).

Table 1: Comparative Efficiency of Organometallic Catalysts Across Reaction Types

References	Metal present in catalyst	Ligands	Solvent	Temperature Range (in °C)	Type of Reaction	Yield (%)	Selectivity (%)	Turn Over Frequency (TOF)	Turn Over Number (TON)	Applications
(25)	Nickel	Diphosphine	Water	25-70°C	Hydrogenation	90	92	450 h ⁻¹	1800	Food industry,

										Fine chemicals
(30)	Palladium	Phosphine	Toluene	80-100°C	Suzuki-Miyaura Cross-Coupling	95	98	500 h ⁻¹	2000	Polymers, Pharmaceuticals
(45)	Platinum	Carbene	Acetone	60-100°C	Oxidation	93	95	480 h ⁻¹	1900	Pharmaceuticals, Materials
(38)	Iron	Nitrogen Ligands	Water	50-90°C	C-H Activation	85	90	400 h ⁻¹	1700	Agrochemicals, Polymers
(46)	Ruthenium	Phosphine or Carbene	Dichloromethane (DCM)	40-90°C	Olefin Metathesis	88	92	470 h ⁻¹	1850	Petrochemicals, Polymers
(63)	Cobalt	Pyridine Ligands	Hexane	200-250°C	Fischer-Tropsch Synthesis	87	91	430 h ⁻¹	1600	Chemicals, Fuels
(70)	Copper	Nitrogen Ligands	Ethanol	100-150°C	Ullman Coupling	83	88	420 h ⁻¹	1500	Electronics, Fine chemicals
(72)	Gold	Phosphine or Carbene	Tetrahydrofuran (THF)	50-90°C	Oxidative Coupling	82	86	410 h ⁻¹	1450	Electronics, Pharmaceuticals
(75)	Silver	Phosphine	Acetonitrile	30-80°C	Alkyne Addition	80	85	400 h ⁻¹	1400	Sensors, Fine Chemicals
(78)	Zinc	Phosphine	Toluene	60-100°C	Hydrosilylation	78	83	380 h ⁻¹	1350	Surface Treatments, Polymers

Table 2: Environmental and Economic Impact of Organometallic Catalysts

References	Metal present in catalyst	Abundance	Energy Requirement	Toxicity	Cost Efficiency	Waste Generation	Recyclability	Green Chemistry Score	Industrial Utilization
(24)	Palladium	Low	High	High	Low	Moderate	Moderate	Moderate	Extensive
(30)	Nickel	High	Low	Low	High	Low	High	High	Moderate
(38)	Iron	High	Low	Low	High	Low	High	High	Moderate
(45)	Platinum	Low	High	High	Low	High	Low	Low	Selective
(46)	Ruthenium	Low	Moderate	Moderate	Low	Moderate	Moderate	Moderate	Specialized
(63)	Cobalt	Moderate	Low	Low	High	Low	High	High	Moderate
(70)	Copper	High	Low	Low	High	Low	High	High	Extensive
(75)	Silver	Low	High	High	Low	Moderate	Low	Moderate	Limited
(72)	Gold	Low	High	High	Low	High	Low	Low	Specialized
(78)	Zinc	High	Low	Low	High	Low	High	High	Moderate

Table 3: Catalytic Activity and Applications Across Different Reaction Types

References	Metal present in catalyst	Reaction Type	Yield (%)	Selectivity (%)	Turn Over Number	Turn Over Frequency	Common Ligands	Solvent	Temperature range in °C.
(24)	Palladium	Suzuki-Miyaura Cross-Coupling	95	98	2000	500 h ⁻¹	Phosphines	Toluene	80-100°C
(30)	Nickel	Hydrogenation	90	92	1800	450 h ⁻¹	Diphosphines	Water	25-70°C

(38)	Iron	C-H Activation	85	90	1700	400 h ⁻¹	Nitrogen Ligands	Water	50-90°C
(45)	Platinum	Oxidation	93	95	1900	480 h ⁻¹	Carbene Ligands	Acetone	60-100°C
(46)	Ruthenium	Olefin Metathesis	88	92	1850	470 h ⁻¹	Phosphine/Carbene Mix	Dichloromethane	40-90°C
(63)	Cobalt	Fischer-Tropsch Synthesis	87	91	1600	430 h ⁻¹	Pyridine Ligands	Hexane	200-250°C
(70)	Copper	Ullmann Coupling	83	88	1500	420 h ⁻¹	Nitrogen Ligands	Ethanol	100-150°C
(75)	Silver	Alkyne Addition	80	85	1400	400 h ⁻¹	Phosphines	Acetonitrile	30-80°C
(72)	Gold	Oxidative Coupling	82	86	1450	410 h ⁻¹	Phosphines/Carbenes	Tetrahydrofuran (THF)	50-90°C
(78)	Zinc	Hydrosilylation	78	83	1350	380 h ⁻¹	Phosphines	Toluene	60-100°C

Discussion

2.1. Analysis of the Data in Tables

In **Table 1**, palladium's superiority in C-C bond formation is evident, but nickel and iron offer sustainable alternatives with competitive yields and lower environmental impact. **Table 2** illustrates that, despite palladium's high toxicity, metals like nickel and iron are more aligned with green chemistry principles due to their recyclability and lower energy requirements. **Table 3** further reinforces that nickel and iron can achieve impressive catalytic efficiency across different reaction types, making them viable alternatives to palladium in many industrial applications.

2.2. Important Findings and Insights

- **Palladium's Efficacy vs. Sustainability:** While palladium remains highly efficient in cross-coupling reactions, its environmental drawbacks and high cost make nickel and iron more attractive for sustainable chemistry.
- **Role of Ligands:** The data show that ligand innovation is crucial in optimizing catalytic performance, particularly in enhancing the activity and selectivity of non-precious metal catalysts like nickel and iron.
- **Computational Insights:** DFT and ML have been instrumental in understanding and optimizing these catalytic systems, guiding experimental work to enhance efficiency and sustainability.

Conclusion

The field of organometallic catalysis has proven to be a pivotal area of research for advancing sustainable chemistry. Our review explored a broad spectrum of transition metal complexes, with a focus on their catalytic efficiencies in diverse reactions such as hydrogenation, dehydrogenation, carbon-carbon bond formation, and carbon dioxide utilization. Through the analysis of 137 papers, it is evident that organometallic catalysts continue to dominate in both academic and industrial settings due to their ability to facilitate highly selective and efficient transformations.

Key Findings:

- 1. Transition Metal Usage:** Palladium, nickel, and copper remain the most frequently used metals in organometallic catalysis, largely due to their remarkable activity in C-C bond formation reactions. Their ability to perform under mild conditions with minimal energy input marks a significant step toward sustainable chemical processes. However, emerging metals like iron and cobalt have also shown considerable promise due to their low cost and abundance, which aligns well with the principles of green chemistry.
- 2. Catalytic Efficiency and Selectivity:** Our findings reveal that the catalytic efficiency of organometallic complexes, particularly palladium- and nickel-based systems, remains unparalleled in hydrogenation and cross-coupling reactions. Their ability to consistently deliver high yields with precise control over selectivity makes them indispensable in the field. In addition, newer studies have highlighted the role of ligand modification in enhancing the catalytic activity, allowing for fine-tuning of reaction conditions and product outcomes.
- 3. Mechanistic Insights:** The mechanistic understanding of organometallic catalysis has deepened significantly, especially in terms of hydrogenation and dehydrogenation processes. Detailed insights into key steps like oxidative addition, reductive elimination, and transmetalation have enabled the design of more robust and versatile catalysts, contributing to the development of more sustainable processes.
- 4. CO₂ Utilization and Sustainability:** One of the most exciting developments is the use of organometallic complexes in carbon dioxide utilization. This advancement not only addresses the global challenge of CO₂ emissions but also provides a pathway to valuable products such as methanol and formic acid. Our review shows that while progress has been made, there are still substantial research gaps, particularly in improving the efficiency and scalability of these processes.

Future Prospects:

As the demand for more environmentally benign processes continues to rise, the role of organometallic catalysts will expand, particularly in green chemistry. Future research should focus on:

- **Expanding the Use of Abundant Metals:** The exploration of earth-abundant metals, such as iron, cobalt, and manganese, is still in its early stages. Further advancements in this area could lead to the discovery of catalysts that are not only more sustainable but also more cost-effective.
- **Integration of Computational Tools:** Advanced computational techniques can be used to predict reaction outcomes and guide experimental efforts, particularly in ligand design and catalyst optimization.
- **Catalysis in Water and Renewable Solvents:** Water-based organometallic catalysis presents a vast opportunity for environmentally friendly chemical processes. Moving forward, increasing the

solubility and stability of organometallic complexes in aqueous and renewable solvent systems will be critical for making these processes more feasible on an industrial scale.

- **CO₂ Conversion and Valorization:** Continued innovation in the catalytic conversion of CO₂ into valuable chemicals will be crucial for addressing environmental sustainability. The challenge remains in increasing the turnover frequency and reducing energy requirements for large-scale applications.

Final Remarks:

Organometallic catalysis remains at the forefront of chemical innovation, bridging the gap between traditional methodologies and the needs of modern sustainable chemistry. The versatility of these catalysts, combined with ongoing advancements in mechanistic understanding and ligand design, ensures their continued relevance in both research and industry. By focusing on the sustainability aspect, this review highlights not only the current capabilities but also the untapped potential of organometallic complexes in driving the next generation of eco-friendly chemical processes. With ongoing research, the field is well-positioned to offer solutions that address some of the most pressing global challenges in energy, environment, and resource management.

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