Open Access

Catalysis Research

Editorial

MOF-based Heterogeneous Catalysis: A Frontier in Sustainable Chemical Transformations

Girijesh Kumar *

Department of Chemistry, University of Allahabad, Prayagraj-211002, Uttar Pradesh, India; E-Mails: girijeshchem@gmail.com; girijeshkumar@allduniv.ac.in

* **Correspondence:** Girijesh Kumar; E-Mails: girijeshchem@gmail.com; girijeshkumar@allduniv.ac.in

Special Issue: Metal-Organic Frameworks in Heterogeneous Catalysis: Recent Progress, New Trends, and Future Perspectives

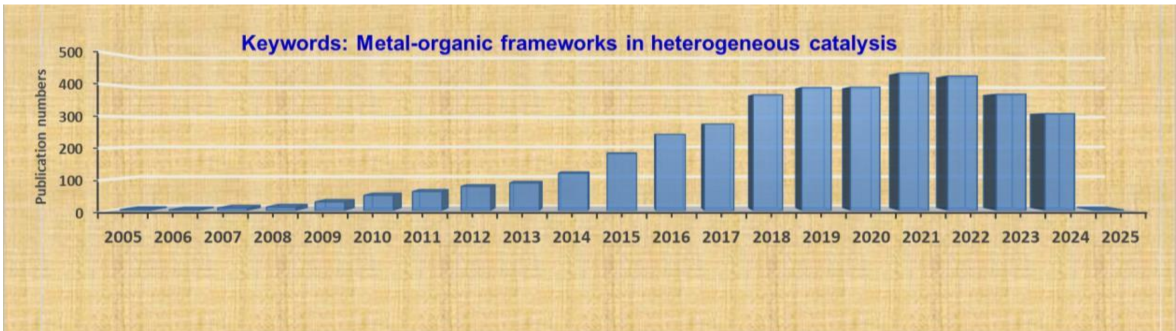
Catalysis Research
2024, volume 4, issue 4
doi:10.21926/cr.2404014

Received: December 02, 2024
Accepted: December 03, 2024
Published: December 05, 2024

Keywords
Metal-organic frameworks; heterogeneous catalysis; enantioselectivity; CO_2 to cyclic carbonates conversion; environmental remediation

The past two decades witnessed significant growth in metal-organic frameworks (MOFs) driven by their intriguing topological architecture and versatile applications such as sensing, sorption, magnetism, drug delivery, and catalysis [1, 2]. Among these, MOF-based catalysis has emerged as a frontier in sustainable chemistry, offering a unique confluence of tunability, structural diversity, and high porosity [3]. These attributes position MOFs as ideal candidates for addressing critical challenges in catalysis, including energy efficiency, environmental sustainability, and the design of selective transformations [4]. MOFs, with their crystalline architectures comprising metal nodes and organic linkers, provide unparalleled opportunities for customization. By modulating the metal center, linker functionality, or overall topology, researchers can design MOFs tailored for specific catalytic reactions. For instance, incorporating Lewis acidic or basic sites enables precise control over reaction pathways, while functionalized linkers facilitate regio- and enantioselective transformations [5]. One of the most compelling properties of MOFs is their ability to act as "heterogenized" homogeneous catalysts. Still, the solid framework offers the advantages of ease of recovery, recyclability, and operational stability [1-5]. This duality allows MOFs to bridge the gap between homogeneous catalysis's precision and heterogeneous systems' practicality.

Since the 1990s, the domain of MOF chemistry has experienced extraordinary growth, marked by a prolific increase in research publications and its continually expanding scope (Figure 1). Over the past decade, numerous research articles, review papers, and authoritative monographs have enriched the literature [1-5]. We believe that this special issue of Catalysis Research is both timely and essential, offering a curated collection of the latest contributions from leading researchers worldwide. This special issue's scope is to publish high-quality papers showcasing noteworthy and cutting-edge developments across all facets of catalysis and catalyzed reactions, including photochemical, electrochemical, environmental, bio-, organo-, nano-, and computational catalysis (Figure 2). We aspire for this collection to serve as an invaluable resource, inspiring both emerging and established researchers in the field.



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Publication numbers	4	3	9	12	28	49	61	77	88	119	182	243	276	369	392	393	438	429	371	309	3

Figure 1 Publication trend of MOFs-based heterogeneous catalysis for the last 20 years (Source: Web of Science: keywords; metal-organic frameworks in heterogeneous catalysis).

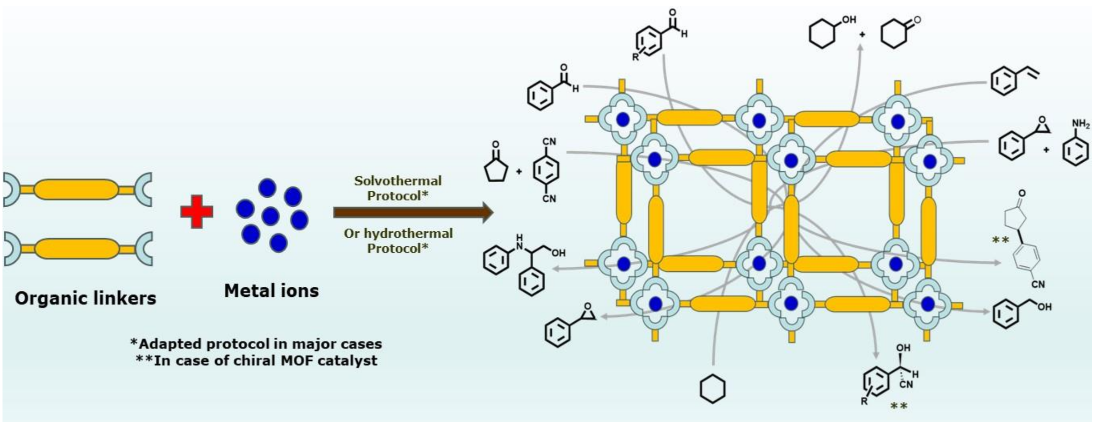


Figure 2 Schematic illustration of the MOF synthesis and their catalytic applications.

Several eminent research groups worldwide made pioneering contributions to the development of the fascinating field of MOF chemistry, including (in no particular order) R. Robson, S. Kitagawa, and O.

M. Yaghi, H. C. Zhou, M. O'Keeffe, M. J. Zaworotko, I. D. Williams, M. W. Hosseini, M. Fujita, S. M. Cohen, X.-M. Chen, C. Ciani, N. R. Champness, G. R. Desiraju, and D. Proserpio [6]. The early exploratory work by these groups not only opened the doors to this field but also laid the foundation for multifunctional MOF chemistry, propelling it to the forefront of materials science and applications. As this special issue focuses on the heterogeneous catalytic applications of MOFs, the next few lines will discuss the growth of MOF-based catalysis. For example, HKUST-1 has shown promise in catalyzing CO_2 to cyclic carbonate conversion, leveraging their significant CO_2 uptake and well-defined catalytic sites [7, 8]. Kumar and co-workers have exploited various Zn- and Cd-MOFs towards CO_2 to cyclic carbonates, as well as detectors for organic amines, flame retardants, nitroaromatics, and antibiotics [9, 10]. In addition, Xu and co-workers have investigated an Ln-MOF for the CO_2 to epoxides cycloaddition reaction and Knoevenagel condensation [11]. Dong and co-workers have exploited a chiral Zr-MOF towards the asymmetric cyanosilylation reaction and obtained promising enantioselectivity [12].

These findings underscore the potential of MOFs to contribute significantly to global carbon management strategies. In addition, MOFs also serve as exceptional platforms for mimicking enzymatic functions. Researchers have replicated the cooperative effects observed in natural enzymes by introducing co-catalysts or co-factors within the framework. This approach has led to breakthroughs in reactions such as C-H activation and oxidative coupling, where traditional catalysts often fall short.

Moreover, the modularity of MOFs allows for the creation of multifunctional reactors. These systems integrate distinct catalytic sites within a single framework, enabling cascade reactions and enhancing overall efficiency [3, 4]. For example, ZIF-based MOFs have been developed to perform sequential oxidations and reductions, streamlining multi-step chemical processes [13]. Despite these advances, challenges remain in scaling up MOF synthesis, improving stability under harsh reaction conditions, and addressing pore blockage during catalysis. Innovative approaches, such as post-synthetic modifications, hybrid materials, and computationally guided design, are crucial to overcoming these hurdles. Furthermore, integrating MOFs with emerging technologies like machine learning could accelerate the discovery of next-generation catalytic materials [14].

In conclusion, MOF-based catalysis is poised to revolutionize chemical industries, offering sustainable solutions for energy conversion, fine chemical synthesis, and environmental remediation. However, translating laboratory-scale innovations to real-world applications requires a multidisciplinary approach, bridging material science, computational chemistry, and process engineering. As researchers continue to unravel the potential of MOFs, this class of materials is set to redefine the boundaries of catalysis, steering us toward a greener and more sustainable future. Let us seize this opportunity to foster collaborations and drive innovations in MOF catalysis, ensuring its profound impact across scientific and industrial landscapes.

Acknowledgments

G Kumar thanks SERB, Government of India, for the financial assistance in the form of the SERB Research Scientist Support Grant with ref No. SB/SRS/2020-21/42/CS. The author also thanks Department of Chemistry, University of Allahabad, Prayagraj, for providing the basic infrastructure to carry out this work.

Author Contributions

The author did all the research work for this study.

Competing Interests

The author declares no conflict of interest.

References

1. Li H, Eddaoudi M, O'Keeffe M, Yaghi OM. Design and synthesis of an exceptionally stable and highly porous metal-organic framework. Nature. 1999; 402: 276-279.
2. Bavykina A, Kolobov N, Khan IS, Bau JA, Ramirez A, Gascon J. Metal–organic frameworks in heterogeneous catalysis: Recent progress, new trends, and future perspectives. Chem Rev. 2020; 120: 8468-8535.
3. Fang Y, Powell JA, Li E, Wang Q, Perry Z, Kirchon A, et al. Catalytic reactions within the cavity of coordination cages. Chem Soc Rev. 2019; 48: 4707-4730.
4. Li D, Yadav A, Zhou H, Roy K, Thanasekaran P, Lee C. Advances and applications of metal-organic frameworks (MOFs) in emerging technologies: A comprehensive review. Glob Chall. 2024; 8: 2300244.
5. Gong W, Chen Z, Dong J, Liu Y, Cui Y. Chiral metal–organic frameworks. Chem Rev. 2022; 122: 9078-9144.
6. Robson R. The historical development of the concepts underlying the design and construction of targeted coordination polymers/MOFs: A personal account. Chem Rec. 2024; 24: e202400038.
7. Yang DA, Cho HY, Kim J, Yang ST, Ahn WS. CO_2 capture and conversion using Mg-MOF-74 prepared by a sonochemical method. Energy Environ Sci. 2012; 5: 6465-6473.
8. Zelenka T, Baláž M, Férová M, Diko P, Bednarčík J, Királyová A, et al. The influence of HKUST-1 and MOF-76 hand grinding/mechanical activation on stability, particle size, textural properties and carbon dioxide sorption. Sci Rep. 2024; 14: 15386.
9. Rani P, Husain A, Bhasin KK, Kumar G. Metal–Organic Framework-based selective molecular recognition of organic amines and fixation of CO_2 into cyclic carbonates. Inorg Chem. 2022; 61: 6977-6994.
10. Rani P, Husain A, Bhasin KK, Kumar G. Zinc (II)-MOF: A versatile luminescent sensor for selective molecular recognition of flame retardants and antibiotics. Inorg Chem. 2024; 63: 3486-3498.
11. Jin S, Fu Y, Jie K, Dai H, Luo YJ, Ye L, et al. High-entropy lanthanide–organic framework as an efficient heterogeneous catalyst for cycloaddition of CO_2 with epoxides and Knoevenagel condensation. Chem Eur J. 2024; 30: e202400756.
12. Jin FZ, Zhao CC, Ma HC, Chen GJ, Dong YB. Homochiral BINAPDA-Zr-MOF for heterogeneous asymmetric cyanosilylation of aldehydes. Inorg Chem. 2019; 58: 9253-9259.
13. Deacon A, Briquet L, Malankowska M, Massingberd-Mundy F, Rudić S, Hyde TL, et al. Understanding the ZIF-L to ZIF-8 transformation from fundamentals to fully costed kilogram-scale production. Commun Chem. 2022; 5: 18.
14. Cohen SM. Postsynthetic methods for the functionalization of Metal–Organic Frameworks. Chem Rev. 2012; 112: 970-1000.