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Transition metal supported UiO-67 materials and their applications in catalysis

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Metal-organic frameworks (MOFs) have emerged as promising platforms for heterogeneous catalysis due to their tunable structures and high specific surface areas. Results indicate that modified composite MOFs not only exhibit superior water stability but also demonstrate broader applicability in catalysis, such as Fenton-like oxidation, Morita-Baylis-Hillman reactions, ethylene dimerization, and various photoelectrochemical processes. Among them, UiO-67, a zirconium-based MOF, has attracted extensive attention for its exceptional chemical stability, high catalytic activity, and well-defined microporous structure. This review introduces composites formed by different types of single and multi-metal loadings on UiO-67 and their demonstrated catalytic performance. It emphasizes the structure-performance relationships of these composites, highlighting how metal loading and spatial distribution influence their reactivity and stability. The current application status and existing challenges of UiO-67 series materials and their derivatives in catalysis are systematically reviewed. By integrating experimental results and mechanistic insights, this work underscores the transformative potential of UiO-67 series materials in meeting the demands of sustainable catalysis.

KEYWORDS

UiO-67, transition metal, catalyst, green chemistry, MOFs

1 Introduction

In the 1990s, the concept of MOFs was introduced by Yaghi et al. (1995). At that time, MOFs had certain limitations in terms of pore size and stability. However, with the passage of time, MOFs, as an emerging material, have undergone remarkable transformations. Over time, MOFs, as an emerging material, have exhibited impressive transformations. Following optimization, MOFs have been capable of maintaining the integrity of their backbone even after the removal of guest molecules from their pores (Li et al., 1999). Furthermore, they have successfully undergone the transition from microporous to mesoporous structures (Rosi et al., 2003). Currently, MOFs have evolved into multifunctional materials characterized by high specific surface area, porosity, large pore size, stable physicochemical properties, and multi-metallic sites. These attributes have facilitated a diverse array of applications for MOFs in areas such as gas adsorption, catalysis, ion separation, and controlled drug release (Mukoyoshi and Kitagawa, 2022; Singh et al., 2021). Based on their structural characteristics, MOFs can be broadly classified into three categories: those containing nitrogen-heterocycles, those containing carboxyl groups, and those incorporating both nitrogen-heterocycles and carboxyl groups.

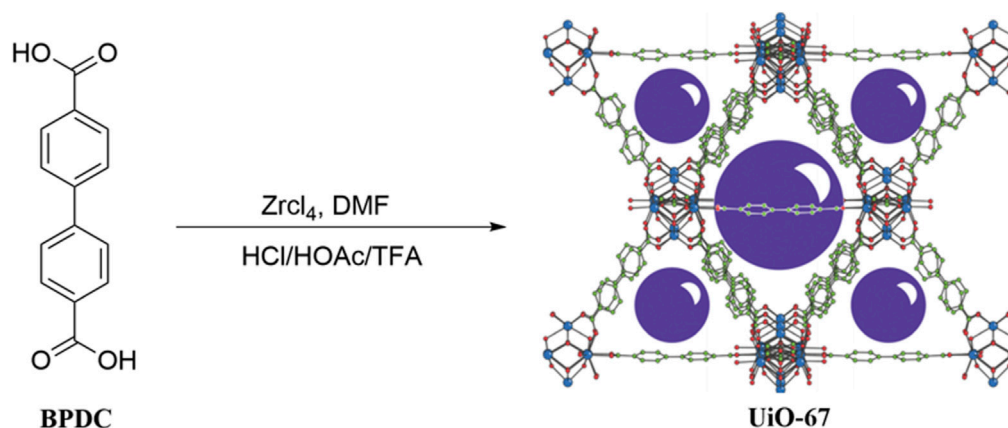


FIGURE 1
Synthesis pathway of UiO-67.

In recent years, MOFs have gained increasing favor among researchers. Notably, the MIL series, ZIF series, and UiO series of MOFs have received widespread attention. Among them, UiO series MOFs have demonstrated remarkable stability under high temperatures, high pressures, and in various solvent environments. It is noteworthy that although most MOFs exhibit unstable qualities in water, UiO series materials are surprisingly stable (Dong et al., 2020; Ogiwara et al., 2019; Piscopo et al., 2019). Therefore, researchers at home and abroad have used UiO series materials as a carrier to explore their catalytic applications by introducing metal ions or other structures to their structures for post-modification studies.

2 Synthesis and preparation of UiO-67

UiO-67, a white microcrystalline powder with the chemical formula $\text{Zr}_6\text{O}_4(\text{OH})_4(\text{BPDC})_6$, is typically synthesized through a hydrothermal method. The standard synthesis procedure is outlined below: Firstly, combine the ligand (4,4'-biphenyldicarboxylic acid), the metal compound (ZrCl_4), and a conditioning acid (such as hydrochloric acid, acetic acid, trifluoroacetic acid, among others). Dissolve the mixture in DMF (N,N-dimethylformamide), then transfer it to a Teflon-lined stainless steel autoclave. Subject the mixture to a reaction for 72 h in a temperature-controlled oven set at 120°C . Upon completion of the reaction, the obtained product undergoes further processing. Subsequently, the product is filtered, washed, and dried to yield the final UiO-67 product (Figure 1).

It was revealed that UiO-67 exhibits a unique structural attribute, featuring octahedral cages that encompass eight tetrahedral cages, with octahedral holes dispersed across both its surface and edges (DeCoste et al., 2013). This peculiar configuration grants UiO-67 an exceptionally high surface area, which can reach as much as $2,200 \text{ m}^2/\text{g}$ (Cavka et al., 2008). Despite variations among researchers in synthetic details, including synthesis temperature, reaction duration, conditioning acid, and the selection of solvents during post-processing (Gutterød et al., 2019; Liu et al., 2018; Cliffe et al., 2017; Zhao et al., 2017), these differences did not have a

significant impact on the fundamental structure of UiO-67. During the synthesis process, the addition of acid can effectively regulate the size and morphology of UiO-67, as well as control its nucleation rate, thus improving the reproducibility of the synthesis (Schaate et al., 2011). In contrast, if no acid is added during the synthesis, the specific surface area of UiO-67 is significantly reduced. In addition, in order to obtain a pure UiO-67 product, washing with DMF and low boiling solvents (e.g., methanol, acetonitrile, etc.) was required to remove unreacted ligands or benzoic acid and to displace the solvent DMF by low-boiling solvents. Lastly, the temperature and duration of the drying, which have a relatively small effect on the structure of the material, were aimed at removing solvents in the pore space for the purpose of activation.

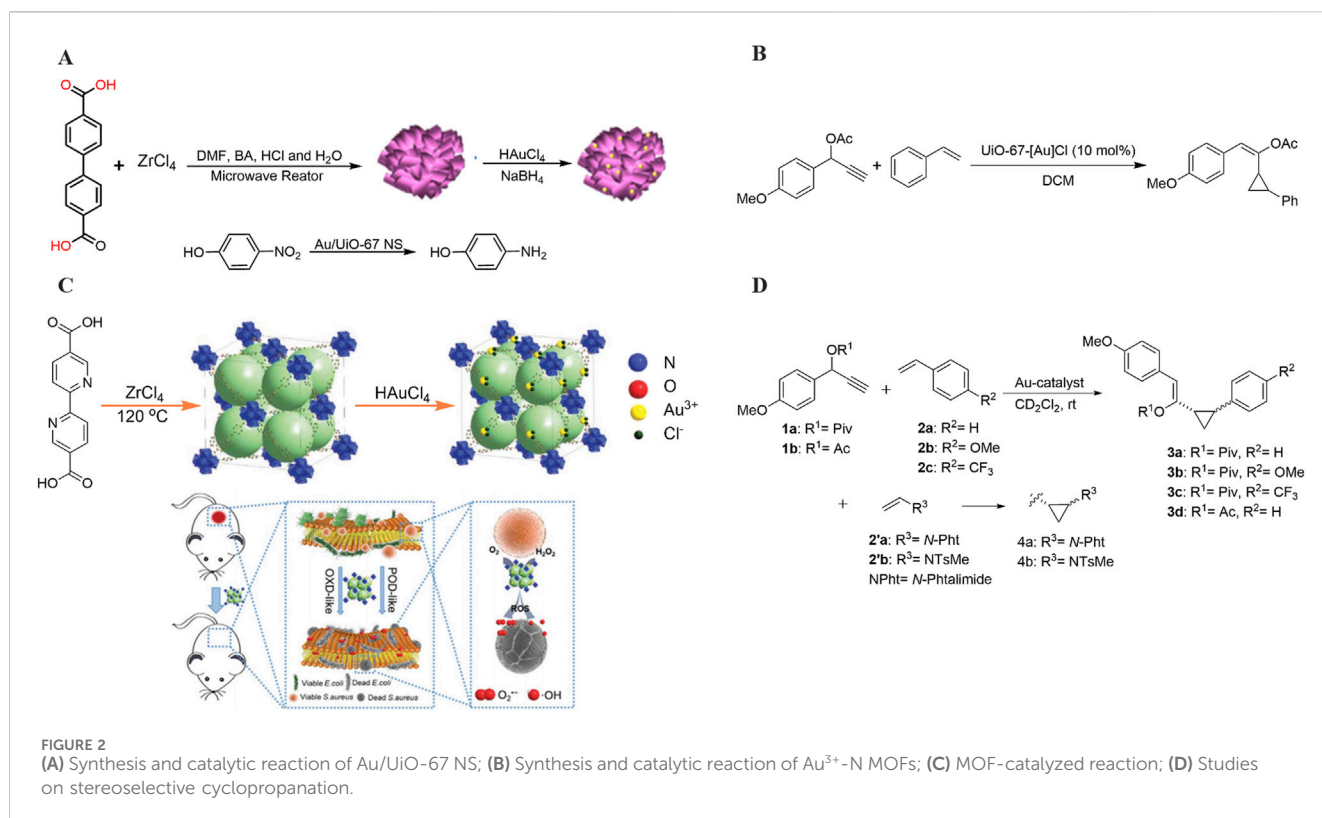
3 Catalytic studies focusing on modifications of UiO-67

3.1 Loading of monometallic complexes on UiO-67

The utilization of MOFs as heterogeneous catalysts is gaining widespread attention, with an increasing focus on incorporating various metals into their frameworks. The literature documents several instances of successfully incorporating a single transition metal into UiO-67, where the modified ligands coordinate with metal ions to yield functionalized MOFs. In this manner, the potential applications of modified UiO-67 in areas like catalysis have been further explored and expanded (Sawano et al., 2015). Nevertheless, the field continues to confront numerous challenges, including the precise control of metal nanocrystal size, position, and arrangement order (Hou C. C. et al., 2015).

3.1.1 Metallic Au and other metal complexes

Haruta et al. (1987) discovered that dispersed gold nanoparticles (Au NPs) exhibit catalytic activity for CO oxidation reactions at low temperatures, sparking widespread interest among researchers in Au nanocatalysts in 1987. With the accelerating advancement of MOFs, there has been speculation about whether loading Au nanoparticles



onto MOFs also imparts catalytic activity. To validate this hypothesis, researchers have repeatedly explored this avenue. In recent years, a more refined approach for Au metallization and modification of UiO-67 materials has emerged, enabling their successful application in catalyzing a diverse range of chemical reactions, including redox reactions and cyclopropanation reactions, among others.

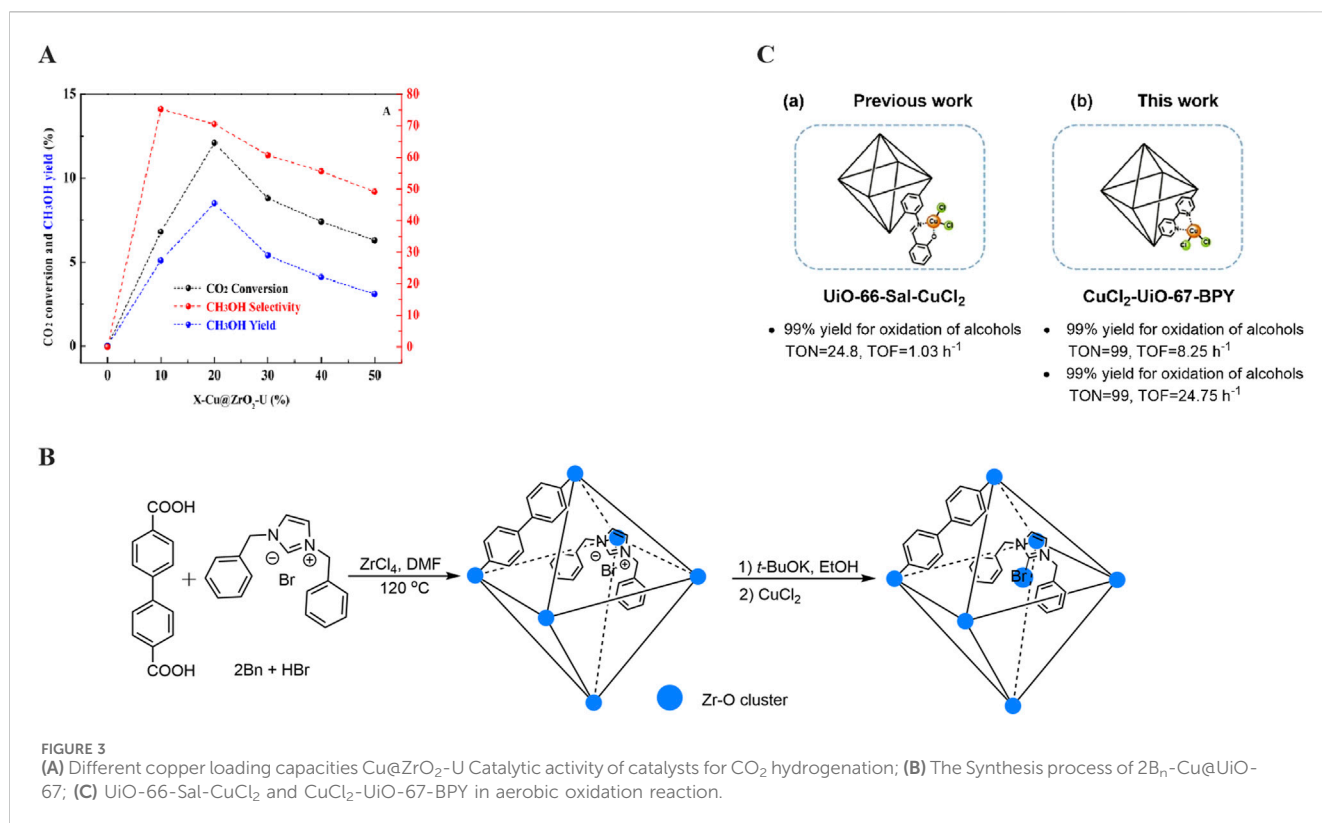
Liu et al. (2022) utilized benzoic acid and hydrochloric acid as modulating acids to swiftly synthesize two-dimensional Zr-MOFs, termed UiO-67 NS, through the application of microwave radiation in 2022 (Figure 2A). In comparison to the conventional solvothermal method, microwave radiation offers the advantages of rapidly and uniformly heating the reaction solution, thereby accelerating the chemical reaction process, markedly enhancing synthesis efficiency, and reducing the overall time required (Mbuya et al., 2022).

Subsequently, the researchers successfully synthesized Au/Uio-67 NS composites through *in situ* reduction of HAuCl₄ within the pores of UiO-67 NS. The experimental findings demonstrated that the resulting nanocomposites exhibited remarkable catalytic activity for the reduction of 4-nitrophenol to 4-aminophenol. With a significant amount of research dedicated to developing synthetic nanomaterials that mimic the advantages of natural enzymes' nanozymes, such as high catalytic activity, biocompatibility, and ease of modification and functionalization (Huang et al., 2019; Jiang et al., 2019; Wu et al., 2019), MOF-based nanozymes have emerged as a key area of focus in this field. In the same year, Pan et al. (2022) successfully coordinated Au³⁺ ions with bipyridine to synthesize Au³⁺-N MOFs materials possessing catalytic properties. It was discovered that these Au³⁺-N MOFs were capable of catalyzing

the aerobic reduction of O₂ to produce superoxide radical anions (O₂^{•−}). Furthermore, they demonstrated peroxidase (POD) activity, forming hydroxyl radicals (•OH) in the presence of H₂O₂. The Au³⁺-modified UiO-67 excelled in catalyzing the production of reactive oxygen species (ROS), thereby enhancing antimicrobial activity without the need for supplementary oxidants. Notably, this material could also be utilized for wound healing, enabling aerobic conditions conducive to green synthesis (Figure 2B).

MOFs can be functionalized not only through the metallization of UiO-67 but also by incorporating pre-modified ligands. Levchenko et al. (2020) chose to anchor the synthesized ligand, Au(L) (OACF)₂ [L = phenylpyridine dicarboxylic di-ester (PPYDE) or phenylpyridine dicarboxylic acid (PPYDC)], onto the UiO-67 backbone, resulting in a UiO-67-[Au]Cl composite. This composite exhibited exceptional catalytic performance in the cyclopropanation reaction (Figure 2C).

It was demonstrated that nearly all the complexes and MOFs exhibited catalytic activity towards the cyclopropanation products, achieving a conversion rate of 97% and demonstrating a preference for the generation of trans diastereoisomers. In contrast, the published literature typically reports that cis-trans isomerization proceeds at varying rates, ultimately leading to the formation of the cis-isomer of the cyclopropanation product (Figure 2D). It is conjectured that this preference for the cis-isomer in the literature may be closely linked to the specific metal complexes and secondary structures employed, as noted in reference (Reiersølmoen et al., 2018). In contrast, this MOF demonstrated high selectivity for the trans isomer in all cyclopropanation reactions, with the cis-to-trans structure ratio of the product remaining relatively constant throughout the reaction period.



These findings indicate that UiO-67-[Au]Cl exhibits a unique stereoselectivity distinct from other Au(III) complexes and maintains its activity for cis-trans isomerization reactions throughout the entire course of the reaction.

3.1.2 Metal Cu and other complexes

With the growing popularity of the concepts of “methanol economy” and “liquid sunshine,” the synthesis of methanol from hydrogen and carbon dioxide derived from renewable energy sources has emerged as one of the most promising approaches for carbon dioxide recycling (Zhong et al., 2020; Niu et al., 2022). Chen et al. (Zhong et al., 2018) utilized the deposition-precipitation (DP) method to prepare Cu@UiO-67, from which a series of Cu@ZrO₂-U catalysts were subsequently derived in 2018. The experimental results revealed that the catalyst activity exhibited a volcano-like trend as the copper doping level increased (Figure 3A). Notably, 20-Cu@ZrO₂-U demonstrated optimal performance in terms of CO₂ conversion, methanol selectivity, and yield, suggesting that a copper content of 20 wt% is the most suitable for the preparation of this catalyst. Furthermore, the abundant presence of Cu⁺ and lattice oxygen in the catalyst promotes the formation of the Cu⁺-ZrO₂ interface, which is a crucial factor in the synthesis of methanol through CO₂ hydrogenation.

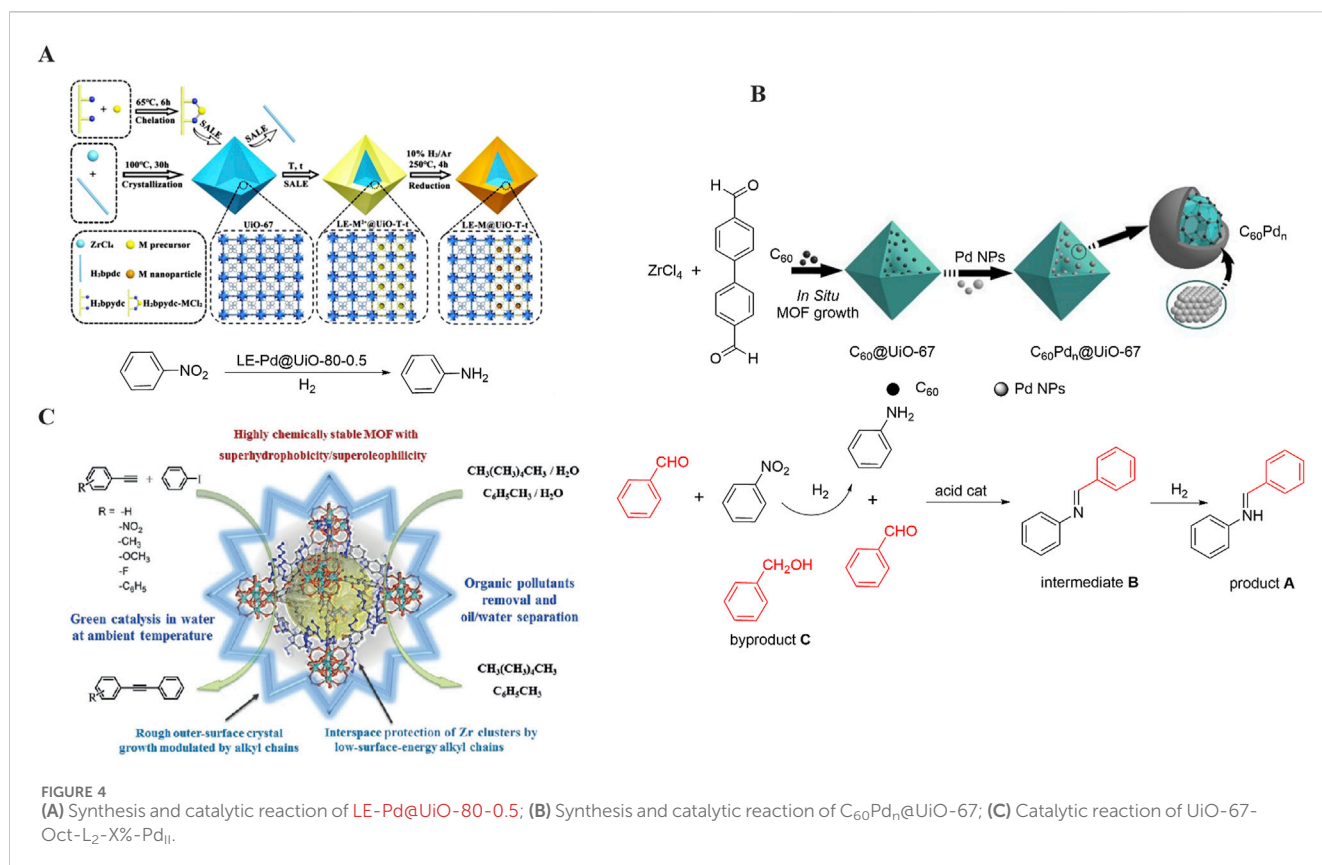
Similarly, Chen et al. (2022) ligated copper single-atom sites (Cu SAS) with N-heterocyclic carbene (NHC) embedded within UiO-67 to obtain the catalyst 2Bn-Cu@UiO-67 (Figure 3B). This catalyst can be employed in electrochemical reactions for the reduction of carbon dioxide (CO₂) to methane. In this material, the enrichment of N-heterocyclic carbene molecules (NHCs) further enhances the surface charge density of the heterogeneous metal

single-atom sites (SASs), thereby intensifying the electrophilic binding and conversion of CO₂. This catalyst design strategy not only offers a novel approach for designing electrocatalytic carbon dioxide reduction reactions but may also provide valuable insights for research in other related fields.

Meanwhile, Cu-loaded UiO-67 can also catalyze aerobic reactions, such as the selective oxidation of alcohols and the epoxidation of olefins. Li R. et al. (2022) successfully synthesized Cu@UiO-67-BPY metal-organic framework materials using a one-pot method in 2022. In a prior study (Hou J. et al., 2015), the research group conducted post-synthetic modification of zirconium-based MOFs UiO-66-NH₂ using salicylaldehyde and immobilized CuCl₂ onto the surface of the functionalized UiO-66-NH₂, yielding the UiO-66-Sal-CuCl₂ material. This catalytic material exhibited effective catalysis in the selective oxidation of benzyl alcohol, achieving a turnover number (TON) of 24.75 and a turnover frequency (TOF) of 1.03 h⁻¹ (Figure 3C). Unfortunately, its application has not yet been expanded to epoxidation reactions. By analyzing the characterization results of the CuCl₂-UiO-67-BPY material in relation to the oxidation of benzyl alcohols catalyzed by various materials, it can be deduced that the presence of the halogen anion facilitates the oxidation process, as the chlorine radical, with its strong electronegativity, aids in the removal of hydrogen. Furthermore, the CuCl₂-UiO-67-BPY catalyst can be recovered and reused at least ten times without significantly compromising its yield or selectivity.

3.1.3 Metal Pd and other complexes

Functionalizing noble metals with MOFs represents a highly promising synthetic approach to combining the porosity and high



specific surface area of MOFs with the elevated catalytic activity of noble metals. This results in the synthesis of catalytic materials that exhibit high catalytic activity while simultaneously reducing catalytic costs (Bugaev et al., 2019). Palladium (Pd), a noble metal, is widely utilized in the preparation of palladium catalysts, which are commonly employed in the chemical industry. These catalysts offer the advantages of high catalytic activity, high selectivity, and low usage, but they also suffer from the disadvantage of a high price. Consequently, numerous researchers have coordinated palladium compounds with MOFs to achieve high catalytic activity while incorporating the benefits of cost reduction.

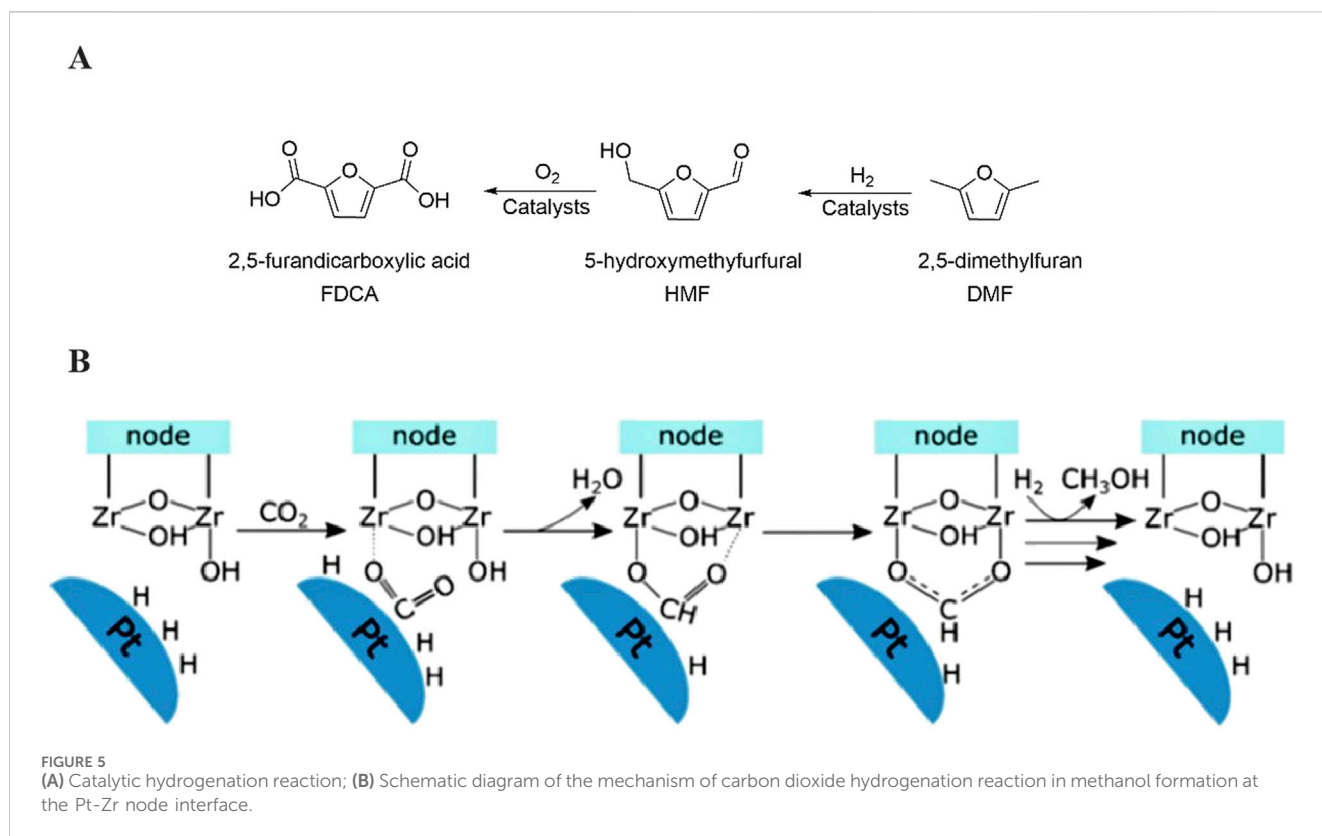
Cui et al. (2021) introduced a solvent-assisted ligand exchange-hydrogen reduction (SALE-HR) strategy to selectively encapsulate ultrafine palladium nanoparticles within the shallow structure of a MOF, specifically UiO-67 in 2021. By precisely controlling factors such as temperature and reaction duration, the thickness of the embedded layer and the size of the metal nanoparticles can be accurately regulated (Figure 4A).

The experimental results demonstrate that the **LE-Pd@UiO-80-0.5** composite materials, featuring the thinnest Pd embedding layer, exhibit superior catalytic performance in the hydrogenation reaction of nitroaromatic hydrocarbons. Specifically, nitrobenzene can be nearly fully converted to aniline, achieving a conversion frequency as high as 600 h⁻¹. This may be attributed to the fact that the metal nanoparticles are embedded as closely as possible to the outer surface of the MOFs, thereby reducing the diffusion distance and consequently enhancing the catalytic activity and utilization efficiency of the **LE-Pd@UiO-80-0.5** material.

Similarly, Zheng D. Y. et al. (2018) successfully modified UiO-67 through Pd metallization, which was subsequently employed to catalyze the hydrogenation reaction. Initially, C₆₀ molecules were encapsulated within the UiO-67 framework, after which Pd NPs were introduced onto C₆₀@UiO-67 utilizing a direct immersion-stirring synthesis method. The method is straightforward, efficient, and significantly enhances the hydrogenation activity of the catalytic reaction owing to the synergistic effect between UiO-67, the encapsulated carbon C₆₀, and the Lewis acid sites provided by UiO-67 (Figure 4B). In comparison to previous literature, C₆₀Pd_n@UiO-67 achieves the same conversion with a shorter duration and milder reaction conditions. The preparation method of this composite paves a new avenue for designing high-catalytic-activity composites based on MOFs, potentially inspiring novel ideas for the construction of functional materials that integrate MOFs with fullerene materials. In addition, Zhu et al. (2019) synthesized (super) hydrophobic MOFs, UiO-67-Oct-L₂-X%-PdII, by incorporating alkyl chains and Pd(II) into the UiO-67 framework. This approach serves a dual purpose: it safeguards the hydrophilic Zr₆O₈ clusters, allowing the MOFs to modulate the surface roughness of the crystal morphology, and endows them with superoleophilicity, thereby achieving superhydrophobicity. Notably, these MOFs can catalyze the Sonogashira reaction at room temperature, exhibiting excellent catalytic efficiency and recyclability (Figure 4C).

3.1.4 Metal Pt and other complexes

In the realm of addressing carbon dioxide pollution, catalytic hydrogenation reactions and methane reactions constitute the



primary research directions (Li et al., 2018; Kattel et al., 2017; Chen X. et al., 2017). Within these reactions, the interplay between metal nanoparticles and MOFs materials holds immense significance for enhancing the catalytic activity and selectivity of the processes.

Hester et al. (2016) successfully loaded Pt nanoparticles (NPs, 0.5 wt%) onto zirconium-based metal-organic frameworks, resulting in the Pt catalyst NP@UiO-67 (dark gray) in 2016. Based on previous literature, this study marks the first in-depth examination of the stability and redox performance of catalysts modified using UiO-series MOFs during the catalytic process. According to previous literature, this represents the first comprehensive investigation into the stability and redox performance of catalysts modified with UiO-series MOFs during the catalytic process. To assess the thermal performance of this composite material, thermogravimetric analysis (TGA) combined with differential thermal analysis (DTA) was employed to compare the UiO-67 composite material with pure UiO-67. The experimental findings revealed that the incorporation of Pt led to a decrease in the thermal stability of the material. However, it is gratifying to note that Pt NP@UiO-67 exhibited higher activity and selectivity in the hydrogenation reaction (Figure 5A). The likely explanation for this phenomenon is that the incorporation of Pt nanoparticles significantly enhances the chemical adsorption of H_2 on UiO-67 at 323 K.

Gutterød et al. (2020) investigated the loading of 3 wt% Pt nanoparticles onto zirconium-based metal-organic frameworks (UiO-67), resulting in UiO-67 Pt in 2020. By enhancing the number of defects in the Zr nodes, the production rates of methanol and methane could be substantially increased. Following this, the team employed infrared steady-state and

transient dynamics, along with spectral and density functional theory (DFT) modeling studies, to thoroughly examine the mechanism of UiO-67-Pt-catalyzed carbon dioxide hydrogenation (Gutterød et al., 2019) (Figure 5B). Previous research has shown that methanol is formed at the interface between defective Zr nodes and Pt nanoparticles (NPs) through the intermediation of formate species attached to the Zr nodes. Besides the activation of hydrogen on Pt NPs, the mechanism of methanol formation is distinct from that of by-product formation, specifically carbon monoxide (CO) and methane.

As a typical precious metal catalyst, Pt has not only been utilized in catalyzing the hydrogenation of carbon dioxide but has also garnered attention in the commercial production of silicon products through silicification reactions (Tondreau et al., 2012). In 2022, Wei et al. (2022) employed a dual ligand-assisted [2,2'-Bipyridine,5,5'-dimethyl (H_2bpydc) and 4,4'-Biphenyldicarboxylic acid (H_2bpdc)] strategy to synthesize a Pt/UiO-67-bpdc catalyst for catalyzing the reaction between alcohols and silane (Table 1). Due to the robust coordination between Pt^{2+} and pyridine on the UiO-67 backbone, highly dispersed Pt sites can be achieved. Additionally, the incorporation of the inert 4,4'-biphenyldicarboxylic acid ligand enhances the overall stability of the material. Conversely, in the absence of this ligand, the Pt/UiO-67-bpdc precursor is susceptible to aggregation during pyrolysis, leading to the formation of Pt nanoparticles. The experimental results demonstrated that the catalyst possessed a high Pt loading content of 0.6962 wt%. During the silane oxidation process, when the Pt loading was decreased to 0.005%, the Pt SAC/N-C catalyst, obtained through high-temperature pyrolysis and acid leaching treatment, exhibited a remarkable transition frequency (TOF) of $9,920 \text{ h}^{-1}$. This catalyst

TABLE 1 Pt SAC/N-C catalyzed reaction between alcohol and silane.

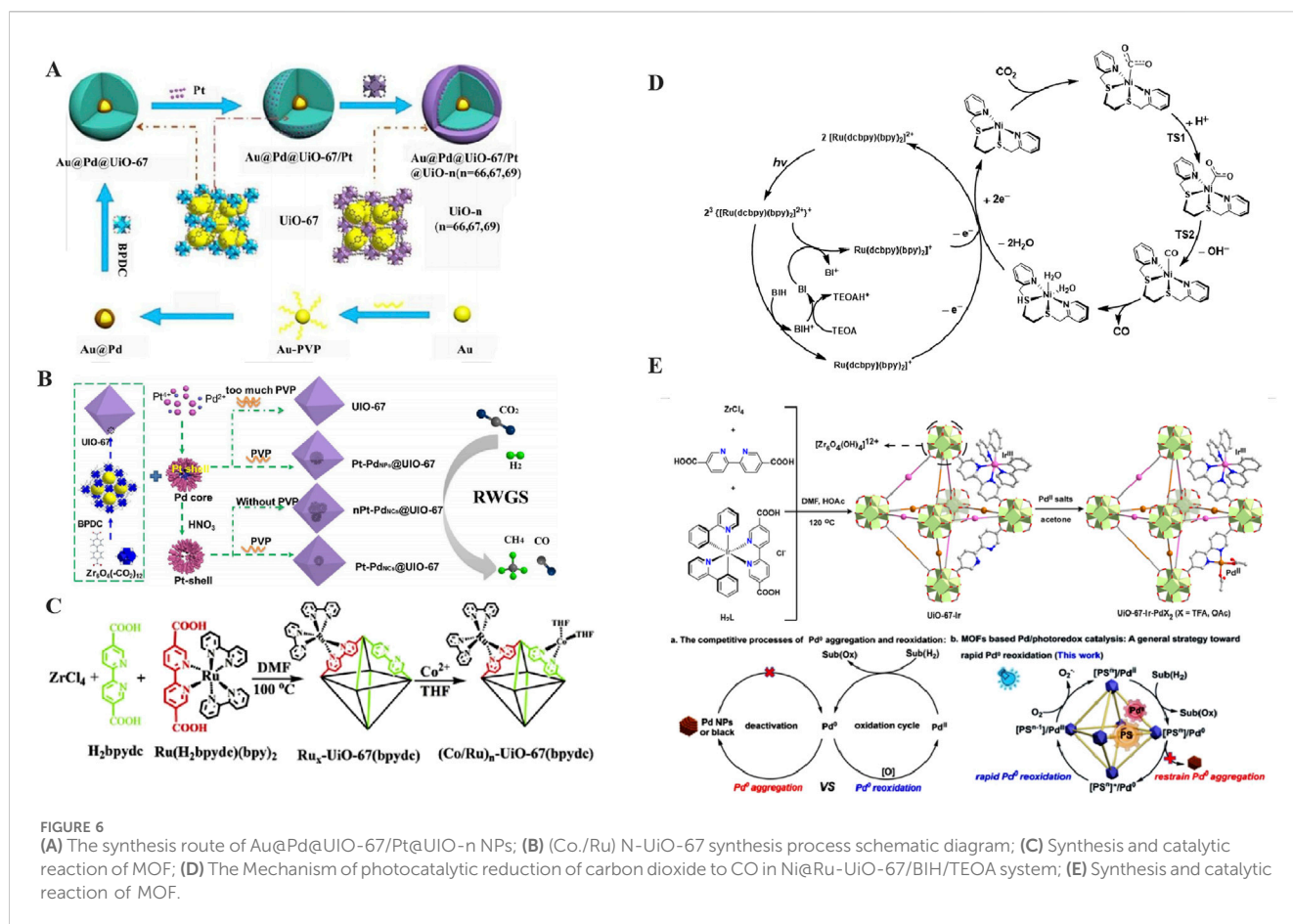
$ \begin{array}{c} R_1 \\ \\ R_2 - SiH \\ \\ R_3 \end{array} + R_4OH \xrightarrow{Pt\ SAC/N-C} \begin{array}{c} R_1 \\ \\ R_2 - Si - OR_4 \\ \\ R_3 \end{array} $				
Entry	Alcohols	Silanes	Reaction time (h)	Conversion (%) ^b
1	Ethanol	Me ₂ PhSiH	3	99.0
2	1-Butanol	Me ₂ PhSiH	3	98.2
3	Ethanol	Et ₃ SiH	3	99.8
4	1-Butanol	Et ₃ SiH	3	98.6
5	Ethanol	Me ₂ (<i>t</i> -Bu)SiH	3	99.5
6	1-Butanol	Me ₂ (<i>t</i> -Bu)SiH	3	98.8
7	Ethanol	Ph ₂ SiH ₂	3	97.5
8	1-Butanol	Ph ₂ SiH ₂	3	96.4

^aReaction conditions: Catalyst Pt SAC/N-C (0.005 mmol of Pt, based on ICP, analysis), silane (10.0 mmol), and alcohols (3.0 mL) were added sequentially to a 10.0 mL round-bottom flask. The mixture was then stirred at 40 °C under a nitrogen atmosphere for 3 h.

^bConversion was determined by GC, analysis.

TABLE 2 Application of UiO-67 series MOFs materials in the field of catalysis.

Materials	Synthesis method	Catalytic applications	Literatures
UiO-66@UiO-67-BPY-Ag	Solvothermal synthesis	Knoevenagel	Gong et al. (2019)
Al@UiO-67	Solvothermal synthesis	Meerwein-Ponndorf-Verley	Larson et al. (2018)
UiO-67-Ce	Solvothermal synthesis	photocatalytic hydrogenation	An et al. (2019)
Ce-doped UiO-67-400	Hydrothermal synthesis	Fenton-like oxidation	Dong et al. (2021)
Co-UiO-67, Re-UiO-67	Solvothermal synthesis	Photocatalytic reduction of carbon dioxide	Gao et al. (2020)
Ni-UiO-67-bpy _{11%}	Solvothermal synthesis	Ethylene dimerization	Komurcu et al. (2021)
Ni-doped UiO-67	Hydrothermal synthesis	Hydrogen Evolution Reaction	Shah et al. (2021)
Ni@UiO-67-NN-P	Solvothermal synthesis	Degradation of methyl orange dye	Li et al. (2020)
UiO-67@Fe	Solvothermal synthesis	Morita-Baylis-Hillman	Zhao et al. (2022a)
FeCl ₃ /UiO-67bpy	Solvothermal synthesis	Catalytic hydrolysis of 5-hydroxymethoxyfurfural	Zhang et al. (2021)
UiO-67-Mix-Ir	Solvothermal synthesis	Boronylation	Yang B. et al. (2019)
UiO-67-supported Ir(C ₂ H ₄) ₂	Solvothermal synthesis	Ethylene dimerization	Yang et al. (2020)
UiO-67-MoO(O ₂) ₂	Solvothermal synthesis	Oxidation of cyclohexane	Hong et al. (2020)
RuB-RuTB-UiO-67	Solvothermal synthesis	Photoelectrochemical oxidation of benzyl alcohol	Lin et al. (2021)
UiO-67-[RuOH ₂] @FTO	Solvothermal synthesis	Electrocatalytic water oxidation reaction	Johnson et al. (2017)
Ru-UiO-67	Solvothermal synthesis	Catalytic water oxidation	Lin et al. (2018)
Rudcbpy-UiO-67(Zr)	Solvothermal synthesis	Photocatalytic debromination reduction	Santiago-Portillo et al. (2018)
TiO ₂ @UiO-67-Zr/Ti	Solvothermal synthesis , Microwave	Photocatalytic oxidation of 5-hydroxymethoxyfurfural	Zhou et al. (2021)
Rh(C ₂ H ₄) ₂ on UiO-67	Solvothermal synthesis	Ethylene hydrogenation and dimerization	Bernales et al. (2017)
Bpy-UiO-Ir	Solvothermal synthesis	C-H bond boronation of aromatic hydrocarbons	Manna et al. (2014)



was successfully employed for the efficient formation of silica-oxygen bonds.

3.1.5 Other metal complexes

The UiO-67 series of MOFs, due to their exceptional thermal stability, are ideal candidates for exploring synthetic functionalization pathways that aim to achieve high catalytic activity while minimizing catalyst costs. It is worth noting that, although noble metals are less commonly utilized as metal nodes in the preparation of MOFs, functional organic ligands possess a significant advantage in coordinating metal ions. Their robust anchoring effect can effectively stabilize noble metal monoatoms. Therefore, numerous researchers have dedicated their efforts to incorporating noble metals (such as Pd, Au, Pt, and Ru) into the UiO-67 metal-organic framework. Furthermore, previous studies have successfully incorporated various metal ions and functional organic ligands (e.g., Al, Ce, Cu, Fe, Ir, Mo, Ni, etc.) into UiO-67 frameworks. Subsequent post-synthetic modification techniques have further expanded the catalytic applications of UiO-67. A summary of representative UiO-67-based MOFs for catalytic purposes is provided in Table 2.

3.2 Loading of polymetallic complexes on UiO-67

Numerous studies have confirmed that multimetallic nanoparticles often display electronic and chemical properties

that are distinctly different from those of monometallic nanoparticles. By combining multiple metals, a synergistic effect can be achieved, thereby enhancing the stability and catalytic activity of the materials (Ferrando et al., 2008; Chen et al., 2005). For instance, bimetallic nanoparticles (BNPs) are renowned for their exceptional catalytic activity in CO₂ hydrogenation.

Xu et al. (2019) successfully synthesized a spherical sandwich catalyst in 2019 (Figure 6A). The material featured Au NPs at its core, with Au@Pd NPs encapsulated within the center of the spherical structure. Subsequently, Pt nanoparticles were loaded onto the surface of this material, resulting in an Au@Pd@UiO-67/Pt composite. Finally, after undergoing additional coating treatment, the ultimate catalyst, Au@Pd@UiO-67/Pt@UiO-67, was obtained. This catalyst was reported to substantially enhance the catalytic activity for CO₂ conversion. Furthermore, the palladium layer adhered to the gold core served to prevent the oxidation of the gold, thereby further improving the stability and activity of the catalyst (Zheng Z. et al., 2018).

In the same year, Liu et al. (2019) also succeeded in synthesizing MOFs loaded with polymetallic nanoparticles, enabling photocatalytic carbon dioxide reduction to syngas (CO and H₂). The team proposed a straightforward two-step self-assembly process to successfully load Co and Ru onto UiO-67, yielding the catalyst (Co/Ru)_n-UiO-67(bpydc) (Figure 6B). By meticulously adjusting the water content and the Co/Ru ratio, they were able to effectively control the H₂ to CO ratio. When the Co/Ru ratio is set to 2.4 and the water content is maintained at 10%, the reaction catalyzed by

(Co/Ru)_{2,4}-UiO-67(bpydc) yields a syngas with an H₂:CO ratio of 2:1. Under these optimal conditions, the yield of high-efficiency syngas can reach as high as 13,600 $\mu\text{mol g}^{-1}$ in 16 h, surpassing the yields achieved by comparable homogeneous catalytic systems. Furthermore, Zhang H. et al. (2020) prepared the octahedral material M@UiO-67 (M = Pt-Pd NPs, Pt NPs), which demonstrated exceptional performance in terms of CO₂ conversion and CO selectivity in RWGS in 2020. Experimental findings indicated that the introduction of acetic acid exerted a marked effect on the morphology of the M@UiO-67 framework. Moreover, polyvinylpyrrolidone (PVP) was shown to effectively regulate both the structural features and dimensional properties of the composite material. (Figure 6C).

Yan et al. (2019) synthesized the composite photocatalyst Ni@Ru-UiO-67, notable for its high activity and selectivity. This photocatalyst can reduce carbon dioxide to CO under visible light illumination, achieving a TON of 581 and a selectivity of up to 99%. Furthermore, the photocatalytic mechanism of Ni@Ru-UiO-67 was thoroughly investigated in this study (Figure 6D). By integrating the findings from ultrafast transient absorption spectra with theoretical calculations, the high catalytic activity observed is attributed to the efficient charge transfer process occurring between Ru-UiO-67 and Ni(II) complexes.

To address the issue of palladium reoxidation, Li J. et al. (2022) incorporated the photosensitizers Ir(III)PS and Pd(II) within the UiO-67 material, thereby constructing a novel molecular conformal material designated as UiO-67-Ir-PdX₂ in 2022. Due to the stabilizing effect of the MOFs framework on the metal sites Pd and Ir, as well as the optimal distance between them which facilitates rapid electron transfer, UiO-67-Ir-PdX₂ exhibits a frequency of Pd-catalyzed conversion under visible light that is 25 times higher compared to existing catalytic systems. The MOF was successfully utilized in a Pd-catalyzed oxidation reaction, fulfilling the objectives of minimizing Pd metal consumption and ensuring recyclability. During the oxidation process, the synergistic effect of Pd⁰ aggregation and the concurrent re-oxidation process facilitated an efficient catalytic cycle (Figure 6E). Specifically, the excitation of Pd⁰ catalysts can serve to decrease the activation energy required for the oxidative addition step. Furthermore, this study anticipates the extension of this strategy to a broader spectrum of transition metals, such as Ru and Rh, offering novel insights for future catalyst design endeavors.

4 Discussion

In recent years, the pharmaceutical industry has increasingly emphasized green chemistry, amidst growing global environmental concerns and gradual energy shortages. The objective is to design synthesis methods for compounds that maximize the incorporation of all materials from the production process into the final product (Sheldon, 2016; Tarasova et al., 2016). For instance, catalysts, which are frequently utilized in chemical reactions, are classified into homogeneous and heterogeneous catalysts based on the phase state of the reaction system (Zhu et al., 2022). The biggest advantage of non-homogeneous catalysts is that they are easy to be separated from the reaction system, which is relative to homogeneous catalysts, and the disadvantage is that the catalytic

efficiency is mostly inferior to homogeneous catalysts, and the reaction is not as easy to be controlled as that of homogeneous catalysts (Poovan et al., 2022), whereas MOFs, as a kind of non-homogeneous catalysts, combine the advantages of non-homogeneous catalysts while compensating for their shortcomings. MOFs possess the following advantages: (1) Their synthesis is straightforward, as the reactivity of metal ions with carboxylic acids and nitrogen-containing heterocyclic ligands is exceptionally high. Additionally, the reaction conditions are mild, allowing for the synthesis of most MOFs in a single step via the solvothermal method. (2) The functional groups and coordination properties of the ligand can be flexibly altered due to the electrostatic interactions between Lewis acids and metal ions. (3) The metal ions that act as backbone vertices have two roles: on the one hand, they act as nodes to provide the backbone's pivot, and on the other hand, they form branches at the pivot nodes, which allow the MOFs backbone to be extended, thus enhancing the physical properties (e.g., porous and chiral) of the MOFs and forming a multidimensional spatial structure (He et al., 2021). (4) When compared with traditional homogeneous catalysts, it can be easily separated and recycled from the reaction system, thereby enabling multiple and repeated cyclic catalytic processes. This characteristic holds significant importance in green catalytic synthesis.

Numerous studies have demonstrated that MOFs exhibit superior performance across diverse applications when compared to traditional porous solid materials, including zeolites and carbon-based porous materials, as referenced in study (Bai et al., 2016). The metal ions within the structural framework of UiO-67 form robust chemical bonds with the organic ligands, endowing it with the ability to withstand structural damage to a certain degree even at elevated temperatures. This attribute grants UiO-67 exceptional high thermal stability, allowing it to maintain its crystalline structure and porous characteristics largely intact when exposed to temperatures below 200°C. Concurrently, these materials possess a significantly larger specific surface area than molecular sieves with comparable pore structures, and they retain the integrity of their backbone even after the solvent molecules within the pores are removed, as indicated in studies (He et al., 2021; Valdebenito et al., 2022; Thür et al., 2019). Zirconium, being abundant in nature and present in all biological systems, along with its low toxicity, further enhances the prospects for the development and application of Zr-MOFs. UiO-66 and UiO-67 are both renowned MOFs. In comparison to UiO-66, UiO-67 structurally substitutes terephthalic acid (bdc) with biphenyl-4,4'-dicarboxylic acid (bpdc). Given that the biphenyl group is elongated relative to the benzene ring, this substitution results in a relatively larger pore size for UiO-67. The enlarged pore size facilitates the diffusion and adsorption of macromolecules, enabling its utilization in the separation or loading of larger molecular species. Consequently, UiO-67 also features a more uniform pore architecture, which empowers it to engage more selectively with specific magnetic guest molecules during adsorption and separation processes, thereby enhancing separation efficacy and adsorption specificity. The UiO-67 series is also celebrated for its surface tunability, stemming from its distinctive structure and chemical composition. These attributes enable the surface to be functionalized through a multitude of approaches, allowing for the customization of its affinity towards various substances, the creation of catalytic active sites, and more, all tailored to meet diverse application

demands. In contrast, UiO-66 exhibits a slightly greater degree of versatility and flexibility when it comes to surface modification. Meanwhile, upon undergoing surface modification, UiO-67 exhibits a surface energy that is more favorable for the binding or dispersion of other substances in certain applications. Furthermore, it catalyzes a broader spectrum of reaction types, particularly in the realm of photoelectrocatalytic hydrogen production, as documented in studies (Bai et al., 2016; Liu, 2020).

Regrettably, we found through extensive literature research that the vast majority of the articles barely investigated the catalytic mechanism. The reason for this is: (1) The structure and composition of MOFs are intricate. Their active sites may be located at the metal center, on a specific group of the ligand, or result from a synergistic effect between the two. Furthermore, the significant variations in pore structure, pore size, and surface properties among different MOFs influence the adsorption of reactant molecules and the reaction pathways, complicating the clear definition and uniform description of the reaction mechanism. Additionally, some MOFs exhibit diverse metal-ligand coordination modes, with the substrate activation mode differing across these modes, further obscuring the determination of the dominant reaction mechanism. (2) Influence of multifaceted factors in the catalytic process: Within MOF catalytic reactions, not only does the intrinsic nature of the MOF itself play a role, but external reaction conditions—such as temperature, pressure, solvent type, and reactant concentration—also exert an influence on the reaction mechanism. Concurrently, MOFs may undergo structural transformations or protonation/deprotonation events during the reaction, thereby augmenting the complexity of mechanism elucidation. (3) Constraints of characterization methodologies: Elucidating the reaction mechanism necessitates the utilization of diverse characterization techniques to glean insights into the intermediary states and active sites involved in the reaction. Nevertheless, contemporary characterization methods are not without their limitations, which hinder the ability to monitor the MOF catalytic reaction process *in situ*, in real time, and with precision. (4) Challenges and substantial expenses associated with mechanism investigation: Delving into the intricacies of MOF catalytic reaction mechanisms demands an integration of experimental methodologies and theoretical computations, encompassing quantum chemical calculations, molecular dynamics simulations, among others, alongside a multitude of controlled experiments. This endeavor is both time-intensive and resource-demanding, incurring significant costs. Certain studies may prioritize practical applications, such as catalyst synthesis, catalytic efficacy, and selectivity, thereby neglecting an in-depth exploration of the reaction mechanism due to constraints imposed by research timelines and resource availability. Consequently, these mechanisms may remain unexplored and thus, are excluded from the article. (5) Ambiguity and discordance surrounding the mechanism: Despite the existence of pertinent research, the mechanism underlying MOF catalytic reactions may remain shrouded in ambiguity or rife with controversy. Varying experimental conditions and research methodologies employed by different research groups often culminate in divergent conclusions, prompting authors to eschew listing the reaction mechanism in favor of emphasizing more definitive research outcomes, such as catalytic performance. This strategic decision

is made to circumvent potential controversies or in instances where the evidence base is insufficiently robust.

In this paper, we discuss the structural properties and catalytic activities of functionalized UiO-67 in general terms, and review the research progress in post-loading transition metal catalysis utilizing this material. Currently, UiO-67 and its structurally modified variants are primarily utilized in applications such as gas separation (Wang et al., 2014; Yan et al., 2021) and storage (Zhao et al., 2022b; Filippousi et al., 2016), drug delivery (Fang et al., 2022; Abazari et al., 2021), heterogeneous catalysis (Ren et al., 2021; Zhang S. et al., 2020; Zhang T. et al., 2020), electrochemistry (Dai et al., 2019; Zhang et al., 2018), and adsorption (Gong et al., 2019; Zhao et al., 2022c). In catalytic applications, UiO-67 materials are frequently employed as carriers for heterogeneous catalysts due to their exceptional stability, multiple coordination sites, ease of functionalization, and high surface area (Tahmouresilard et al., 2018; Wei et al., 2018; Yang X. et al., 2019). There are four main pathways for the synthesis of UiO-67: Modulated synthesis (Cavka et al., 2008), Isorecticular expansion (Bae et al., 2010; Liu et al., 2015), Topology-guided design (Gutov et al., 2014), Postsynthetic functionalization (Savonnet et al., 2010). Typically, the catalytically active component can be incorporated into the MOFs framework through the method of ligand pre-modification, where the pre-modified ligand subsequently coordinates with metal ions to form functionalized MOFs. By adopting this approach, the catalytically active metal component is orderly embedded within the MOFs pores, effectively preventing the leakage and aggregation of the active catalytic substance during the catalytic process.

It has been demonstrated that loading metal nanoparticles (such as Pd, Ir, Ru, Co., among others) onto UiO-67 can substantially enhance the conversion of greenhouse gases like carbon dioxide and methane into non-hazardous gases. Additionally, numerous researchers have concentrated their efforts on transition metals like Au, Cu, Pd, Pt, and others, which exhibit exceptional performance in catalyzing reactions such as cyclopropanation, benzylic alcohol oxidation, and the Suzuki coupling/asymmetric aldol reactions. Furthermore, there are researchers who are intrigued by metal complexes such as Al, Ce, Ni, Fe, Mo, Ti, and others, which are loaded onto the surface of UiO-67 MOF and employed to catalyze reactions like the Morita-Baylis-Hillman reaction, Fenton-like reaction, as well as a range of photocatalytic and electrocatalytic reactions (Cao et al., 2020; Cheng et al., 2022; Zhuo et al., 2021; Li Y. et al., 2022; Lü et al., 2020; Masoomi et al., 2019). Based on our literature review, we observed that the majority of catalytic applications involving UiO-67 are predominantly in the photocatalytic domain, as detailed in Table 3. In a manner analogous to the preceding discussion, the current state of mechanistic research on UiO-67 series metal organic frameworks in photocatalytic reactions is somewhat lacking. Consequently, there is significant scope for in depth investigation into the internal electron and energy transfer processes within these materials during photocatalysis. This exploration can be conducted from multiple perspectives, including the transfer of electrons from organic ligands to the central metal, inter-atomic electron transfer within the central metal cluster, and the broader electron and energy transfer dynamics in the context of photocatalysis. Currently, researchers in the field of photocatalytic water splitting

TABLE 3 Applications of UiO-67 series MOFs in photocatalytic field.

Materials	Synthesis method	Applications	Literatures
Eu ³⁺ -UiO-67	Solvothermal synthesis	Detect Ag ⁺ Fluorescent Sensor	Luo et al. (2021)
Ru (bpy) ₃ ²⁺ -UiO-67	Solvothermal synthesis	Immunosensor for the detection of hexestrol (DES)	(Dong et al., 2018)
Ru (bpy) ₃ ²⁺ -UiO-67	Solvothermal synthesis	Therapeutic nanoplatfrom for <i>in vitro</i> two-photon fluorescence imaging and photodynamic therapy	Chen R. et al. (2017)
ZA-MPTMS-Eu-UiO-67	Solvothermal synthesis	Fluorescence detection of ammonia vapors	Ma and Yan (2019)
Ru(II)(bpy) ₂ (dcbpy)-doped UiO-67	Solvothermal synthesis	Ruthenium doping ratio and photocatalytic mechanism	Zhu et al. (2017), Maza et al. (2016), Maza et al. (2014)
Ru(dcbpy)-UiO-67	Solvothermal synthesis	Photocatalytic debromination of α -bromone	Santiago-Portillo et al. (2018)
UiO-67-ZnPc	Hydrothermal synthesis, Microwave method	Photocatalytic oxidation of naphthoquinones	Lü et al. (2020)
UiO-67-Ru	Hydrothermal synthesis	Photocatalytic synthesis of β -acetylaminopropenyl sulfone	Xu et al. (2020)
UiO-67	Solvothermal synthesis	Liquid Chromatography Fluorescence Detection	Liu et al. (2016)
SRB@UiO-66 SRB@UiO-67	Solvothermal synthesis	Good cellular dyes and laser materials	Ruan et al. (2020)
UiO-67	Solvothermal synthesis	Degradation of anionic organic dyes	Zhang et al. (2018)
UiO-67	Hydrothermal synthesis	photocatalytic hydrogenation	Sun et al. (2020)
CsPbX ₃ @UiO-67	Solvothermal synthesis	White LED devices	Zhang et al. (2019)

predominantly focus on the semi-reactive process of hydrogen production *via* water photolysis in the presence of a sacrificial agent. However, there is a notable dearth of studies investigating the complete decomposition of water using single MOFs. Beyond conventional strategies such as constructing heterojunctions or incorporating loaded catalysts, the challenge of achieving total photocatalytic water decomposition using a single MOF framework represents a pivotal research frontier. Overcoming this hurdle holds immense significance and research value, as it could unlock new possibilities for harnessing MOFs in water - splitting applications. These studies not only broaden the application scope of UiO-67 MOF materials in catalysis but also offer novel insights and solutions for addressing environmental challenges.

5 Conclusion

We discovered that existing techniques possess the capability to precisely control the composition of nodes, the substitution pattern of connectors, and the defect density within modified UiO-67. Among the numerous known MOFs, UiO-67 distinguishes itself with exceptional properties: catalysts synthesized within its framework demonstrate remarkable selectivity and catalytic activity in various chemical reactions, capable of undergoing at least five rounds of recycling, thereby aligning perfectly with the principles of green chemistry (Hu et al., 2019; Valdebenito et al., 2022). However, we also acknowledge the limitations of the current study: (1) the majority of UiO-67 derivatives primarily catalyze relatively well-established reactions, with a notable lack of in-depth investigation into their catalytic mechanisms (Das et al., 2019; Zwolinski and Chmielewski, 2017). (2) during the catalyst recycling process, a certain amount of

catalyst is inevitably lost due to operations such as extraction and filtration (Li et al., 2024). (3) The majority of MOFs have yet to be applied to industrial production on a large scale and are still in the nascent stages of commercialization. These are questions that need to be further explored in the next scientific studies. The potential of UiO-67 is, undeniably, geared towards fostering its broader utilization within the realm of multidisciplinary chemistry (Zhou et al., 2025). Presently, existing research endeavors are unevenly allocated across various applications, with a predominant emphasis on catalysis. Future research endeavors will concentrate on broadening the applications of the Zr-UiO-67 across diverse domains. This includes delving deeper into its utility in carbon dioxide capture and conversion, as well as organic transformations. Additionally, investigations will extend to its role in water treatment, environmental remediation, biosensing, serving as porous carriers, facilitating drug delivery, and enabling energy storage solutions. Extensive research centered around UiO-67 has demonstrated its boundless potential for commercial applications. Upon achieving practical implementation, this advancement will signify a monumental leap forward in the evolution of UiO-67 materials.

Author contributions

TL: Writing – original draft, Writing – review and editing. YL: Writing – review and editing. JM: Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Abazari, R., Esrafil, L., Morsali, A., Wu, Y., and Gao, J. (2021). $\text{PMo}_{12}\text{@UiO-67}$ nanocomposite as a novel *non*-leaching catalyst with enhanced performance durability for sulfur removal from liquid fuels with exceptionally diluted oxidant. *Appl. Catal. B Environ.* 283, 119582. doi:10.1016/j.apcatb.2020.119582
- An, Y., Liu, Y., Bian, H., Wang, Z., Wang, P., Zheng, Z., et al. (2019). Improving the photocatalytic hydrogen evolution of UiO-67 by incorporating Ce^{4+} -coordinated bipyridinedicarboxylate ligands. *Sci. Bull.* 64 (20), 1502–1509. doi:10.1016/j.scib.2019.07.030
- Bae, Y. S., Yazaydin, A. O., and Snurr, R. Q. (2010). Evaluation of the BET method for determining surface areas of MOFs and zeolites that contain ultra-micropores. *Langmuir* 26 (8), 5475–5483. doi:10.1021/la100449z
- Bai, Y., Dou, Y., Xie, L. H., Rutledge, W., Li, J. R., and Zhou, H. C. (2016). Zr-based metal-organic frameworks: design, synthesis, structure, and applications. *Chem. Soc. Rev.* 45 (8), 2327–2367. doi:10.1039/c5cs00837a
- Bernales, V., Yang, D., Yu, J., Gümüşlü, G., Cramer, C. J., Gates, B. C., et al. (2017). Molecular rhodium complexes supported on the metal-oxide-like nodes of metal organic frameworks and on Zeolite HY: catalysts for ethylene hydrogenation and dimerization. *ACS Appl. Mater. and Interfaces* 9 (39), 33511–33520. doi:10.1021/acsami.7b03858
- Bugaev, A. L., Skorynina, A. A., Braglia, L., Lomachenko, K. A., Guda, A., Lazzarini, A., et al. (2019). Evolution of Pt and Pd species in functionalized UiO-67 metal-organic frameworks. *Catal. Today* 336, 33–39. doi:10.1016/j.cattod.2019.03.054
- Cao, C. S., Wang, J., Yu, X., Zhang, Y., and Zhu, L. (2020). Photodegradation of seven bisphenol analogues by $\text{Bi}_2\text{O}_3/\text{UiO-67}$ heterojunction: relationship between the chemical structures and removal efficiency. *Appl. Catal. B Environ.* 277, 119222. doi:10.1016/j.apcatb.2020.119222
- Cavka, J. H., Jakobsen, S., Olsbye, U., Guillou, N., Lamberti, C., Bordiga, S., et al. (2008). A new zirconium inorganic building brick forming metal organic frameworks with exceptional stability. *J. Am. Chem. Soc.* 130 (42), 13850–13851. doi:10.1021/ja8057953
- Chen, M., Kumar, D., Yi, C. W., and Goodman, D. W. (2005). The promotional effect of gold in catalysis by palladium-gold. *Science* 310 (5746), 291–293. doi:10.1126/science.1115800
- Chen, R., Zhang, J., Chelora, J., Xiong, Y., Kershaw, S. V., Li, K. F., et al. (2017). Ruthenium (II) complex incorporated UiO-67 metal-organic framework nanoparticles for enhanced two-photon fluorescence imaging and photodynamic cancer therapy. *ACS Appl. Mater. and interfaces* 9 (7), 5699–5708. doi:10.1021/acsami.6b12469
- Chen, S., Li, W. H., Jiang, W., Yang, J., Zhu, J., Wang, L., et al. (2022). MOF encapsulating *N*-heterocyclic carbene-ligated copper single-atom site catalyst towards efficient methane electrosynthesis. *Angew. Chem. Int. Ed.* 61 (4), e202114450. doi:10.1002/anie.202114450
- Chen, X., Su, X., Duan, H., Liang, B., Huang, Y., and Zhang, T. (2017). Catalytic performance of the Pt/TiO_2 catalysts in reverse water gas shift reaction: controlled product selectivity and a mechanism study. *Catal. Today* 281, 312–318. doi:10.1016/j.cattod.2016.03.020
- Cheng, L., Cao, L., Ren, H., Guo, Q., Deng, H., and Li, Y. (2022). Pd (II)-Metalated and l-proline-decorated multivariate UiO-67 as bifunctional catalyst for asymmetric sequential reactions. *Catal. Lett.* 152 (4), 1160–1169. doi:10.1007/s10562-021-03719-0
- Cliffe, M. J., Castillo-Martinez, E., Wu, Y., Lee, J., Forse, A. C., Firth, F. C. N., et al. (2017). Metal-organic nanosheets formed via defect-mediated transformation of a hafnium metal-organic framework. *J. Am. Chem. Soc.* 139 (15), 5397–5404. doi:10.1021/jacs.7b00106
- Cui, Z., Fan, T., Chen, L., Fang, R., Li, C., and Li, Y. (2021). Encapsulation of ultrafine Pd nanoparticles within the shallow layers of UiO-67 for highly efficient hydrogenation reactions. *Sci. China Chem.* 64 (1), 109–115. doi:10.1007/s11426-020-9881-7
- Dai, G., Li, Z., Luo, F., Ai, S., Chen, B., and Wang, Q. (2019). Electrochemical determination of *Salmonella typhimurium* by using aptamer-loaded gold nanoparticles and a composite prepared from a metal-organic framework (type UiO-67) and graphene. *Microchim. Acta* 186 (9), 620–629. doi:10.1007/s00604-019-3724-y
- Das, A., Anbu, N., Dhakshinamoorthy, A., and Biswas, S. (2019). Highly active urea-functionalized Zr (IV)-UiO-67 metal-organic framework as hydrogen bonding heterogeneous catalyst for Friedel-Crafts alkylation. *Inorg. Chem.* 58 (8), 5163–5172. doi:10.1021/acs.inorgchem.9b00259
- DeCoste, J. B., Peterson, G. W., Jasuja, H., Glover, T. G., Huang, Y. g., and Walton, K. S. (2013). Stability and degradation mechanisms of metal-organic frameworks containing the $\text{Zr}_6\text{O}_4(\text{OH})_4$ secondary building unit. *J. Mater. Chem. A* 1 (18), 5642–5650. doi:10.1039/c3ta10662d
- Dong, M. J., Wang, X., and Wu, C. D. (2020). Creation of redox-active PdS_x nanoparticles inside the defect pores of MOF UiO-66 with unique semihydrogenation catalytic properties. *Adv. Funct. Mater.* 30 (7), 1908519. doi:10.1002/adfm.201908519
- Dong, X., Lin, Y., Ren, G., Ma, Y., and Zhao, L. (2021). Catalytic degradation of methylene blue by fenton-like oxidation of Ce-doped MOF. *Colloids Surfaces A Physicochem. Eng. Aspects* 608, 125578. doi:10.1016/j.colsurfa.2020.125578
- Dong, X., Zhao, G., Liu, L., Li, X., Wei, Q., and Cao, W. (2018). Ultrasensitive competitive method-based electrochemiluminescence immunosensor for diethylstilbestrol detection based on $\text{Ru}(\text{bpy})_3^{2+}$ as luminophore encapsulated in metal-organic frameworks UiO-67. *Biosens. Bioelectron.* 110, 201–206. doi:10.1016/j.bios.2018.03.066
- Fang, F., Lv, Q., Li, P., Tao, Y., Zhang, Y., Zhou, Y., et al. (2022). Screening of hierarchical porous UiO-67 for efficient removal of glyphosate from aqueous solution. *J. Environ. Chem. Eng.* 10 (3), 107824. doi:10.1016/j.jece.2022.107824
- Ferrando, R., Jellinek, J., and Johnston, R. L. (2008). Nanoclusters: from theory to applications of alloy clusters and nanoparticles. *Chem. Rev.* 108 (3), 845–910. doi:10.1021/cr040090g
- Filippousi, M., Turner, S., Leus, K., Siafaka, P. I., Tseligka, E. D., Vandichel, M., et al. (2016). Biocompatible Zr-based nanoscale MOFs coated with modified poly (ϵ -caprolactone) as anticancer drug carriers. *Int. J. Pharm.* 509 (1–2), 208–218. doi:10.1016/j.ijpharm.2016.05.048
- Gao, X., Guo, B., Guo, C., Meng, Q., Liang, J., and Liu, J. (2020). Zirconium-based metal-organic framework for efficient photocatalytic reduction of CO_2 to CO: the influence of doped metal ions. *ACS Appl. Mater. and Interfaces* 12 (21), 24059–24065. doi:10.1021/acsami.0c05631
- Gong, Y., Yuan, Y., Chen, C., Zhang, P., Wang, J., Khan, A., et al. (2019). Enhancing catalytic performance via structure core-shell metal-organic frameworks. *J. Catal.* 375, 371–379. doi:10.1016/j.jcat.2019.06.031
- Gutov, O. V., Bury, W., Gomez-Gualdrón, D. A., Krungleviciute, V., Fairen-Jimenez, D., Mondloch, J. E., et al. (2014). Water-stable zirconium-based metal-organic framework material with high-surface area and gas-storage capacities. *Chemistry-A Eur. J.* 20 (39), 12389–12393. doi:10.1002/chem.201402895
- Gutterød, E. S., Lazzarini, A., Fjermestad, T., Kaur, G., Manzoli, M., Bordiga, S., et al. (2019). Hydrogenation of CO_2 to methanol by Pt nanoparticles encapsulated in UiO-67: deciphering the role of the metal-organic framework. *J. Am. Chem. Soc.* 142 (2), 999–1009. doi:10.1021/jacs.9b10873

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- Gutterød, E. S., Pulumati, S. H., Kaur, G., Lazzarini, A., Solemsli, B. G., Gunnæs, A. E., et al. (2020). Influence of defects and H₂O on the hydrogenation of CO₂ to methanol over Pt nanoparticles in UiO-67 metal-organic framework. *J. Am. Chem. Soc.* 142 (40), 17105–17118. doi:10.1021/jacs.0c07153
- Haruta, M., Kobayashi, T., Sano, H., and Yamada, N. (1987). Novel gold catalysts for the oxidation of carbon monoxide at a temperature far below 0 °C. *Chem. Lett.* 16 (2), 405–408. doi:10.1246/cl.1987.405
- He, H., Li, R., Yang, Z., Chai, L., Jin, L., Alhassan, S. I., et al. (2021). Preparation of MOFs and MOFs derived materials and their catalytic application in air pollution: a review. *Catal. Today* 375, 10–29. doi:10.1016/j.cattod.2020.02.033
- Hester, P., Xu, S., Liang, W., Al-Janabi, N., Vakili, R., Hill, P., et al. (2016). On thermal stability and catalytic reactivity of Zr-based metal-organic framework (UiO-67) encapsulated Pt catalysts. *J. Catal.* 340, 85–94. doi:10.1016/j.jcat.2016.05.003
- Hong, Y., Peng, J., Sun, Z., Yu, Z., Wang, A., Wang, Y., et al. (2020). Transition metal oxodiperoxocomplex modified metal-organic frameworks as catalysts for the selective oxidation of cyclohexane. *Materials* 13 (4), 829. doi:10.3390/ma13040829
- Hou, C. C., Li, T. T., Cao, S., Chen, Y., and Fu, W. F. (2015). Incorporation of a [Ru(dcbpy)(bpy)]²⁺ photosensitizer and a Pt (dcbpy)Cl₂ catalyst into metal-organic frameworks for photocatalytic hydrogen evolution from aqueous solution. *J. Mater. Chem. A* 3 (19), 10386–10394. doi:10.1039/c5ta01135c
- Hou, J., Luan, Y., Tang, J., Wensley, A. M., Yang, M., and Lu, Y. (2015). Synthesis of UiO-66-NH₂ derived heterogeneous copper (II) catalyst and study of its application in the selective aerobic oxidation of alcohols. *J. Mol. Catal. A Chem.* 407, 53–59. doi:10.1016/j.molcata.2015.06.018
- Hu, M. L., Masoomi, M. Y., and Morsali, A. (2019). Template strategies with MOFs. *Coord. Chem. Rev.* 387, 415–435. doi:10.1016/j.ccr.2019.02.021
- Huang, Y., Ren, J., and Qu, X. (2019). Nanozymes: classification, catalytic mechanisms, activity regulation, and applications. *Chem. Rev.* 119 (6), 4357–4412. doi:10.1021/acs.chemrev.8b00672
- Jiang, D., Ni, D., Rosenkrans, Z. T., Huang, P., Yan, X., and Cai, W. (2019). Nanozyme: new horizons for responsive biomedical applications. *Chem. Soc. Rev.* 48 (14), 3683–3704. doi:10.1039/c8cs00718g
- Johnson, B. A., Bhunia, A., and Ott, S. (2017). Electrocatalytic water oxidation by a molecular catalyst incorporated into a metal-organic framework thin film. *Dalton Trans.* 46 (5), 1382–1388. doi:10.1039/c6dt03718f
- Kattel, S., Liu, P., and Chen, J. G. (2017). Tuning selectivity of CO₂ hydrogenation reactions at the metal/oxide interface. *J. Am. Chem. Soc.* 139 (29), 9739–9754. doi:10.1021/jacs.7b05362
- Komurcu, M., Lazzarini, A., Kaur, G., Borfecchia, E., Øien-Ødegaard, S., Gianolio, D., et al. (2021). Co-catalyst free ethene dimerization over Zr-based metal-organic framework (UiO-67) functionalized with Ni and bipyridine. *Catal. Today* 369, 193–202. doi:10.1016/j.cattod.2020.03.038
- Larson, P. J., Cheney, J. L., French, A. D., Klein, D. M., Wylie, B. J., and Cozzolino, A. F. (2018). Anchored aluminum catalyzed meerwein-ponndorf-verley reduction at the metal nodes of robust MOFs. *Inorg. Chem.* 57 (12), 6825–6832. doi:10.1021/acs.inorgchem.8b00119
- Levchenko, V. A., Siah, H. S. M., Øien-Ødegaard, S., Kaur, G., Fiksdahl, A., and Tilst, M. (2020). Catalytic studies of cyclometalated gold (III) complexes and their related UiO-67 MOF. *Mol. Catal.* 492, 111009. doi:10.1016/j.mcat.2020.111009
- Li, H., Eddaoudi, M., O'Keeffe, M., and Yaghi, O. M. (1999). Design and synthesis of an exceptionally stable and highly porous metal-organic framework. *Nature* 402 (6759), 276–279. doi:10.1038/46248
- Li, J., He, L., Liu, Q., Ren, Y., and Jiang, H. (2022). Visible light-driven efficient palladium catalyst turnover in oxidative transformations within confined frameworks. *Nat. Commun.* 13 (1), 928–1013. doi:10.1038/s41467-022-28474-7
- Li, R., Li, X., Ramella, D., Zhao, Y., and Luan, Y. (2022). An efficient and recyclable Cu@UiO-67-BPY catalyst for the selective oxidation of alcohols and the epoxidation of olefins. *New J. Chem.* 46 (12), 5839–5847. doi:10.1039/d2nj00225f
- Li, T., Li, N., and Shi, D. (2024). A highly efficient and recyclable CuI@ UiO-67-bpy catalyst for direct sp² C–H arylation of azoles. *New J. Chem.* 48 (46), 19418–19426. doi:10.1039/d4nj03726j
- Li, W., Wang, H., Jiang, X., Zhu, J., Liu, Z., Guo, X., et al. (2018). A short review of recent advances in CO₂ hydrogenation to hydrocarbons over heterogeneous catalysts. *R. Soc. Chem. Adv.* 8 (14), 7651–7669. doi:10.1039/c7ra13546g
- Li, Y., Y., Zhai, G., Liu, Y., Wang, Z., Wang, P., Zheng, Z., et al. (2022). Synergistic effect between boron containing metal-organic frameworks and light leading to enhanced CO₂ cycloaddition with epoxides. *Chem. Eng. J.* 437, 135363. doi:10.1016/j.cej.2022.135363
- Li, Z., Zhang, H., Kong, L., Chen, Z., Yang, Y., Liu, X., et al. (2020). Coordination and space confined preparation of nickel sub-nanoparticles within a metal-organic framework for catalytic degradation of methyl orange. *J. Environ. Chem. Eng.* 8 (5), 104363. doi:10.1016/j.jece.2020.104363
- Lin, S., Cairnie, D. R., Davis, D., Chakraborty, A., Cai, M., and Morris, A. J. (2021). Photoelectrochemical alcohol oxidation by mixed-linker metal-organic frameworks. *Faraday Discuss.* 225, 371–383. doi:10.1039/d0fd00021c
- Lin, S., Ravari, A. K., Zhu, J., Usov, P. M., Cai, M., Ahrenholtz, S. R., et al. (2018). Insight into metal-organic framework reactivity: chemical water oxidation catalyzed by a [Ru-(tpy)(dcbpy)(OH₂)]²⁺-modified UiO-67. *Chem. Sustain. Energy Mater.* 11 (2), 464–471. doi:10.1002/cssc.201701644
- Liu, L., Xia, L., Wu, C., Qu, F., Li, G., Sun, Z., et al. (2016). Zirconium (IV)-based metal organic framework (UiO-67) as efficient sorbent in dispersive solid phase extraction of plant growth regulator from fruits coupled with HPLC fluorescence detection. *Talanta* 154, 23–30. doi:10.1016/j.talanta.2016.03.038
- Liu, M., Mu, Y. F., Yao, S., Guo, S., Guo, X. W., Zhang, Z. M., et al. (2019). Photosensitizing single-site metal-organic framework enabling visible-light-driven CO₂ reduction for syngas production. *Appl. Catal. B Environ.* 245, 496–501. doi:10.1016/j.apcatb.2019.01.014
- Liu, S., Xu, J., Dai, E., Qiu, J., and Liu, Y. (2018). Synthesis and properties of ferrocene confined within UiO-67 MOFs. *Microporous Mesoporous Mater.* 264, 133–138. doi:10.1016/j.micromeso.2018.01.018
- Liu, T. F., Feng, D., Chen, Y. P., Zou, L., Bosch, M., Yuan, S., et al. (2015). Topology-guided design and syntheses of highly stable mesoporous porphyrinic zirconium metal-organic frameworks with high surface area. *J. Am. Chem. Soc.* 137 (1), 413–419. doi:10.1021/ja5111317
- Liu, X. (2020). Metal-organic framework UiO-66 membranes. *Front. Chem. Sci. Eng.* 14, 216–232. doi:10.1007/s11705-019-1857-5
- Liu, X., Li, Y., Liu, Y., Li, S., Feng, L., Zhuang, J., et al. (2022). Microwave-assisted synthesis of 2D Zr-MOF nanosheets supported gold nanocomposites as efficient catalysts for the reduction of 4-nitrophenol. *J. Alloys Compd.* 922, 165939. doi:10.1016/j.jallcom.2022.165939
- Lü, C. X., Zhan, G. P., Chen, K., Liu, Z. K., and Wu, C. D. (2020). Anchoring Zn-phthalocyanines in the pore matrices of UiO-67 to improve highly the photocatalytic oxidation efficiency. *Appl. Catal. B Environ.* 279, 119350. doi:10.1016/j.apcatb.2020.119350
- Luo, J., Liu, B. S., Zhang, X. R., and Liu, R. T. (2021). A new fluorescent sensor constructed by Eu³⁺ post-functionalized metal-organic framework for sensing Ag⁺ with high selectivity and sensitivity in aqueous solution. *J. Mol. Struct.* 1227, 129518. doi:10.1016/j.molstruc.2020.129518
- Ma, J., and Yan, B. (2019). Multi-component luminescence responsive Eu³⁺/Tb³⁺ hybrids based with metal-organic frameworks and zeolites A. *Spectrochimica Acta Part A Mol. Biomol. Spectrosc.* 220, 117107. doi:10.1016/j.saa.2019.05.012
- Manna, K., Zhang, T., and Lin, W. (2014). Postsynthetic metalation of bipyridyl-containing metal-organic frameworks for highly efficient catalytic organic transformations. *J. Am. Chem. Soc.* 136 (18), 6566–6569. doi:10.1021/ja5018267
- Masoomi, M. Y., Morsali, A., Dhakshinamoorthy, A., and Garcia, H. (2019). Mixed-metal MOFs: unique opportunities in metal-organic framework (MOF) functionality and design. *Angew. Chem. Int. Ed.* 131 (43), 15330–15347. doi:10.1002/ange.201902229
- Maza, W. A., Ahrenholtz, S. R., Epley, C. C., Day, C. S., and Morris, A. J. (2014). Solvothermal growth and photophysical characterization of a ruthenium (II) tris (2, 2'-bipyridine)-doped zirconium UiO-67 metal organic framework thin film. *J. Phys. Chem. C* 118 (26), 14200–14210. doi:10.1021/jp5034195
- Maza, W. A., Haring, A. J., Ahrenholtz, S. R., Epley, C. C., Lin, S. Y., and Morris, A. J. (2016). Ruthenium (II)-polypyridyl zirconium (IV) metal-organic frameworks as a new class of sensitized solar cells. *Chem. Sci.* 7 (1), 719–727. doi:10.1039/c5sc01565k
- Mbuya, C. O. L., Jewell, L. L., Ntelane, T. S., and Scurrall, M. S. (2022). The effect of microwave irradiation on heterogeneous catalysts for Fischer-Tropsch synthesis. *Rev. Chem. Eng.* 38, 721–736. doi:10.1515/revce-2020-0017
- Mukoyoshi, M., and Kitagawa, H. (2022). Nanoparticle/metal-organic framework hybrid catalysts: elucidating the role of the MOF. *Chem. Commun.* 58 (77), 10757–10767. doi:10.1039/d2cc03233c
- Niu, J., Liu, H., Jin, Y., Fan, B., Qi, W., and Ran, J. (2022). Comprehensive review of Cu-based CO₂ hydrogenation to CH₃OH: insights from experimental work and theoretical analysis. *Int. J. Hydrogen Energy* 47, 9183–9200. doi:10.1016/j.ijhydene.2022.01.021
- Ogiwara, N., Kobayashi, H., Concepción, P., Rey, F., and Kitagawa, H. (2019). The first study on the reactivity of water vapor in metal-organic frameworks with platinum nanocrystals. *Angew. Chem. Int. Ed.* 131 (34), 11857–11862. doi:10.1002/anie.201905667
- Pan, M. M., Ouyang, Y., Song, Y. L., Si, L., Jiang, M., Yu, X., et al. (2022). Au³⁺-Functionalized UiO-67 metal-organic framework nanoparticles: O₂^{•−} and ·OH generating nanozymes and their antibacterial functions. *Small* 18 (23), 2200548. doi:10.1002/smll.202200548
- Piscopo, C. G., Voellinger, L., Schwarzer, M., Polyzoidis, A., Bošković, D., and Loebbecke, S. (2019). Continuous flow desulfurization of a model fuel catalyzed by titanium functionalized UiO-66. *ChemistrySelect* 4 (9), 2806–2809. doi:10.1002/slct.201900342
- Poovan, F., Chandrashekar, V., Natte, K., and Jagadeesh, R. V. (2022). Synergy between homogeneous and heterogeneous catalysis. *Catal. Sci. and Technol.* 12 (22), 6623–6649. doi:10.1039/d2cy00232a
- Reiersølmoen, A. C., Østrem, E., and Fiksdahl, A. (2018). Gold (III)-Catalysed cis-to-trans cyclopropyl isomerization. *Eur. J. Org. Chem.* 2018 (25), 3317–3325. doi:10.1002/ejoc.201800419

- Ren, H., Cheng, L., Yang, J., Zhao, K., Zhai, Q., and Li, Y. (2021). Recyclable and reusable chiral α , α -l-diaryl prolinol heterogeneous catalyst grafting to UiO-67 for enantioselective hydration/aldol/oxa-Diels Alder domino reaction. *Catal. Commun.* 149, 106249. doi:10.1016/j.catcom.2020.106249
- Rosi, N. L., Eckert, J., Eddaoudi, M., Vodak, D. T., Kim, J., O'Keeffe, M., et al. (2003). Hydrogen storage in microporous metal-organic frameworks. *Science* 300 (5622), 1127–1129. doi:10.1126/science.1083440
- Ruan, B., Liu, H. L., Xie, L., Ding, H., Zhang, Y., Wu, J., et al. (2020). The fluorescence property of zirconium-based MOFs adsorbed sulforhodamine B. *J. Fluoresc.* 30, 427–435. doi:10.1007/s10895-020-02531-0
- Santiago-Portillo, A., Baldovi, H. G., Carbonell, E., Navalón, S., Álvaro, M., García, H., et al. (2018). Ruthenium (II) tris (2, 2'-bipyridyl) complex incorporated in UiO-67 as photoredox catalyst. *J. Phys. Chem. C* 122 (51), 29190–29199. doi:10.1021/acs.jpcc.8b07204
- Savonnet, M., Bazer-Bachi, D., Bats, N., Perez-Pellitero, J., Jeanneau, E., Lecocq, V., et al. (2010). Generic postfunctionalization route from amino-derived metal-organic frameworks. *J. Am. Chem. Soc.* 132 (13), 4518–4519. doi:10.1021/ja909613e
- Sawano, T., Ji, P., McIsaac, A. R., Lin, Z., Abney, C. W., and Lin, W. (2015). The first chiral diene-based metal-organic frameworks for highly enantioselective carbon-carbon bond formation reactions. *Chem. Sci.* 6 (12), 7163–7168. doi:10.1039/c5sc02100f
- Schaate, A., Roy, P., Godt, A., Lippke, J., Waltz, F., Wiebcke, M., et al. (2011). Modulated synthesis of Zr-based metal-organic frameworks: from nano to single crystals. *Chemistry-A Eur. J.* 17 (24), 6643–6651. doi:10.1002/chem.201003211
- Shah, W. A., Ibrahim, S., Abbas, S., Naureen, L., Batool, M., Imran, M., et al. (2021). Nickel containing polyoxometalates incorporated in two different metal-organic frameworks for hydrogen evolution reaction. *J. Environ. Chem. Eng.* 9 (5), 106004. doi:10.1016/j.jece.2021.106004
- Sheldon, R. A. (2016). Green chemistry and resource efficiency: towards a green economy. *Green Chem.* 18 (11), 3180–3183. doi:10.1039/c6gc90040b
- Singh, R., Kumar, B., Sahu, R. K., Kumari, S., Jha, C. B., Singh, N., et al. (2021). Development of a pH-sensitive functionalized metal organic framework: *in vitro* study for simultaneous delivery of doxorubicin and cyclophosphamide in breast cancer. *R. Soc. Chem. Adv.* 11 (53), 33723–33733. doi:10.1039/d1ra04591a
- Sun, S., Liao, P., Zeng, L., He, L., and Zhang, J. (2020). UiO-67 metal-organic gel material deposited on photonic crystal matrix for photoelectrocatalytic hydrogen production. *RSC Adv.* 10 (25), 14778–14784. doi:10.1039/d0ra00868k
- Tahmouresilerd, B., Larson, P. J., Unruh, D. K., and Cozzolino, A. F. (2018). Make room for iodine: systematic pore tuning of multivariate metal-organic frameworks for the catalytic oxidation of hydroquinones using hypervalent iodine. *Catal. Sci. and Technol.* 8 (17), 4349–4357. doi:10.1039/c8cy00794b
- Tarasova, N. P., Makarova, A. S., and Ingel, F. I. (2016). Systemic approach to the development of green chemistry. *Pure Appl. Chem.* 88 (1–2), 37–42. doi:10.1515/pac-2015-0701
- Thür, R., Van Velthoven, N., Sloodmaekers, S., Didden, J., Verbeke, R., Smolders, S., et al. (2019). Bipyridine-based UiO-67 as novel filler in mixed-matrix membranes for CO₂-selective gas separation. *J. Membr. Sci.* 576, 78–87. doi:10.1016/j.memsci.2019.01.016
- Tondreau, A. M., Atienza, C. C. H., Weller, K. J., Nye, S. A., Lewis, K. M., Delis, J. G. P., et al. (2012). Iron catalysts for selective anti-Markovnikov alkene hydrosilylation using tertiary silanes. *Science* 335 (6068), 567–570. doi:10.1126/science.1214451
- Valdebenito, G., González-Carvajal, M., Santibañez, L., and Cancino, P. (2022). Metal-organic frameworks (MOFs) and materials derived from MOFs as catalysts for the development of green processes. *Catalysts* 12 (2), 136. doi:10.3390/catal12020136
- Wang, B., Huang, H., Lv, X. L., Xie, Y., Li, M., and Li, J. R. (2014). Tuning CO₂ selective adsorption over N₂ and CH₄ in UiO-67 analogues through ligand functionalization. *Inorg. Chem.* 53 (17), 9254–9259. doi:10.1021/ic5013473
- Wei, Q., Sun, Y., Wang, S., Hu, Z., Liu, Q., and Zheng, X. (2022). Construction of highly dispersed Pt single sites and high-efficiency-heterocatalysis silylation of alcohols with silanes. *Nano Res.* 16, 4643–4649. doi:10.1007/s12274-022-5097-5
- Wei, Y. L., Li, Y., Chen, Y. Q., Dong, Y., Yao, J. J., Han, X. Y., et al. (2018). Pd (II)-NHDC-Functionalized UiO-67 type MOF for catalyzing heck cross-coupling and intermolecular benzyne-benzyne-alkene insertion reactions. *Inorg. Chem.* 57 (8), 4379–4386. doi:10.1021/acs.inorgchem.7b03271
- Wu, J., Wang, X., Wang, Q., Lou, Z., Li, S., Zhu, Y., et al. (2019). Nanomaterials with enzyme-like characteristics (nanozymes): next-generation artificial enzymes (II). *Chem. Soc. Rev.* 48 (4), 1004–1076. doi:10.1039/c8cs00457a
- Xu, H. T., Luo, X. K., Wang, J. J., Su, Y., Zhao, X., and Li, Y. (2019). Spherical sandwich Au@Pd@UiO-67/Pt@UiO-*n* (*n* = 66, 67, 69) core-shell catalysts: Zr-based metal-organic frameworks for effectively regulating the reverse water-gas shift reaction. *ACS Appl. Mater. and Interfaces* 11 (22), 20291–20297. doi:10.1021/acsami.9b04748
- Xu, S., Kong, H., and Zhang, R. (2020). Visible-light-induced, UiO-67-Ru-catalyzed oxidative cross-coupling for constructing β -acetylamino acrylosulfones. *Tetrahedron Lett.* 61 (11), 151629. doi:10.1016/j.tetlet.2020.151629
- Yaghi, O. M., Li, G., and Li, H. (1995). Selective binding and removal of guests in a microporous metal-organic framework. *Nature* 378 (6558), 703–706. doi:10.1038/378703a0
- Yan, F., Wang, Q., Wang, F., and Huang, Z. (2021). Study on energy storage properties of Metal-organic frameworks nanofluids (UiO-67/Water and UiO-67/Methanol) by an experimental and theoretical method. *J. Mater. Sci.* 56 (16), 10008–10017. doi:10.1007/s10853-021-05910-5
- Yan, Z. H., Ma, B., Li, S. R., Liu, J., Chen, R., Du, M. H., et al. (2019). Encapsulating a Ni (II) molecular catalyst in photoactive metal-organic framework for highly efficient photoreduction of CO₂. *Sci. Bull.* 64 (14), 976–985. doi:10.1016/j.scib.2019.05.014
- Yang, B., Wu, X. P., Gagliardi, L., and Truhlar, D. G. (2019). Methane functionalization by an Ir (III) catalyst supported on a metal-organic framework: an alternative explanation of steric confinement effects. *Theor. Chem. Accounts* 138 (9), 107–111. doi:10.1007/s00214-019-2498-y
- Yang, D., Gaggioli, C. A., Conley, E., Babucci, M., Gagliardi, L., and Gates, B. C. (2020). Synthesis and characterization of tetrairidium clusters in the metal organic framework UiO-67: catalyst for ethylene hydrogenation. *J. Catal.* 382, 165–172. doi:10.1016/j.jcat.2019.11.031
- Yang, X., Wang, S., Yang, N., Zhou, W., Wang, P., Jiang, K., et al. (2019). Oxygen vacancies induced special CO₂ adsorption modes on Bi₂MoO₆ for highly selective conversion to CH₄. *Appl. Catal. B Environ.* 259, 118088. doi:10.1016/j.apcatb.2019.118088
- Zhang, D., Zhao, J., Liu, Q., and Xia, Z. (2019). Synthesis and luminescence properties of CsPbX₃@ UiO-67 composites toward stable photoluminescence converters. *Inorg. Chem.* 58 (2), 1690–1696. doi:10.1021/acs.inorgchem.8b03295
- Zhang, H., Xu, H., Li, Y., and Su, Y. (2020). Octahedral core-shell bimetallic catalysts M@ UiO-67 (M= Pt-Pd nanoparticles, Pt-Pd nanocages): metallic nanocages that enhanced CO₂ conversion. *Appl. Mater. Today* 19, 100609. doi:10.1016/j.apmt.2020.100609
- Zhang, M., Lou, J., Xu, R., Li, P., Sha, Y., Zhang, H., et al. (2021). Post-synthetic anchoring Fe (III) into a fcu-type Zr-MOF for the catalyzed hydrolysis of 5-hydroxylmethoxyfurfural. *Microporous Mesoporous Mater.* 328, 111449. doi:10.1016/j.micromeso.2021.111449
- Zhang, R. Z., Huang, Y., Zhang, W., and Yang, J. M. (2018). Effect of particle size distribution of UiO-67 nano/microcrystals on the adsorption of organic dyes from aqueous solution. *CrystEngComm* 20 (38), 5672–5676. doi:10.1039/c8ce01295d
- Zhang, S., Wang, Y., Cao, Z., Xu, J., Hu, J., Huang, Y., et al. (2020). Simultaneous enhancements of light-harvesting and charge transfer in UiO-67/CdS/rGO composites toward ofloxacin photo-degradation. *Chem. Eng. J.* 381, 122771. doi:10.1016/j.cej.2019.122771
- Zhang, T., Wei, J. Z., Sun, X. J., Zhao, X. J., Tang, H. I., Yan, H., et al. (2020). Continuous and rapid synthesis of UiO-67 by electrochemical methods for the electrochemical detection of hydroquinone. *Inorg. Chem.* 59 (13), 8827–8835. doi:10.1021/acs.inorgchem.0c00580
- Zhao, Q., Du, Q., Yang, Y., Zhao, Z., Cheng, J., Bi, F., et al. (2022b). Effects of regulator ratio and guest molecule diffusion on VOCs adsorption by defective UiO-67: experimental and theoretical insights. *Chem. Eng. J.* 433, 134510. doi:10.1016/j.cej.2022.134510
- Zhao, Q., Zhao, Z., Rao, R., Yang, Y., Ling, S., Bi, F., et al. (2022c). Universitet i Oslo-67 (UiO-67)/graphite oxide composites with high capacities of toluene: synthesis strategy and adsorption mechanism insight. *J. Colloid Interface Sci.* 627, 385–397. doi:10.1016/j.jcis.2022.07.059
- Zhao, W., Zhang, C., Yan, Z., Zhou, Y., Li, J., Xie, Y., et al. (2017). Preparation, characterization, and performance evaluation of UiO-66 analogues as stationary phase in HPLC for the separation of substituted benzenes and polycyclic aromatic hydrocarbons. *Public Lib. Sci.* 12 (6), e0178513. doi:10.1371/journal.pone.0178513
- Zhao, Y., Zhu, M., Shang, H., Cheng, Y., Ramella, D., Zhu, K., et al. (2022a). UiO-67 metal-organic framework immobilized Fe³⁺ catalyst for efficient Morita-Baylis-Hillman reaction. *New J. Chem.* 46 (7), 3199–3206. doi:10.1039/d1nj04544j
- Zheng, D. Y., Zhou, X. M., Mutyala, S., and Huang, X. (2018). High catalytic activity of C₆₀Pd_n encapsulated in metal-organic framework UiO-67, for tandem hydrogenation reaction. *Chemistry-A Eur. J.* 24 (72), 19141–19145. doi:10.1002/chem.201803900
- Zheng, Z., Xu, H., Xu, Z., and Ge, J. (2018). A monodispersed spherical Zr-based metal-organic framework catalyst, Pt/Au@Pd@UiO-66, comprising an Au@Pd core-shell encapsulated in a UiO-66 center and its highly selective CO₂ hydrogenation to produce CO. *Small* 14 (5), 1702812. doi:10.1002/sml.201702812
- Zhong, G., Liu, D., and Zhang, J. (2018). Incorporation of functional groups expands the applications of UiO-67 for adsorption, catalysis and thiols detection. *ChemistrySelect* 3 (25), 7066–7080. doi:10.1002/slct.201800840
- Zhong, J., Yang, X., Wu, Z., Liang, B., Huang, Y., and Zhang, T. (2020). State of the art and perspectives in heterogeneous catalysis of CO₂ hydrogenation to methanol. *Chem. Soc. Rev.* 49 (5), 1385–1413. doi:10.1039/c9cs00614a
- Zhou, J., Gu, S., Xiang, Y., Xiong, Y., and Liu, G. (2025). UiO-67: a versatile metal-organic framework for diverse applications. *Coord. Chem. Rev.* 526, 216354. doi:10.1016/j.ccr.2024.216354

Zhou, Y., Liu, J., and Long, J. (2021). Photocatalytic oxidation 5-Hydroxymethylfurfural to 2, 5-diformylfuran under air condition over porous TiO₂@MOF. *J. Solid State Chem.* 303, 122510. doi:10.1016/j.jssc.2021.122510

Zhu, J., Maza, W. A., and Morris, A. J. (2017). Light-harvesting and energy transfer in ruthenium (II)-polypyridyl doped zirconium (IV) metal-organic frameworks: a look toward solar cell applications. *J. Photochem. Photobiol. A Chem.* 344, 64–77. doi:10.1016/j.jphotochem.2017.04.025

Zhu, N. X., Wei, Z. W., Chen, C. X., Wang, D., Cao, C., Qiu, Q., et al. (2019). Self-generation of surface roughness by low-surface-energy alkyl chains for highly stable superhydrophobic/superoleophilic MOFs with multiple functionalities. *Angew. Chem. Int. Ed.* 131 (47), 17189–17196. doi:10.1002/ange.201909912

Zhu, Q., Gu, Y., Wang, X., Zhang, C., and Ma, J. (2022). Discovery of electronic structure and interfacial interaction features in catalytic activity. *Langmuir ACS J. Surfaces Colloids* 38 (13), 3959–3968. doi:10.1021/acs.langmuir.2c00176

Zhuo, T. C., Song, Y., Zhuang, G. L., Chang, L. P., Yao, S., Zhang, W., et al. (2021). H-bond-mediated selectivity control of formate versus CO during CO₂ photoreduction with two cooperative Cu/X sites. *J. Am. Chem. Soc.* 143 (16), 6114–6122. doi:10.1021/jacs.0c13048

Zwolinski, K. M., and Chmielewski, M. J. (2017). TEMPO-appended metal-organic frameworks as highly active, selective, and reusable catalysts for mild aerobic oxidation of alcohols. *ACS Appl. Mater. and Interfaces* 9 (39), 33956–33967. doi:10.1021/acsami.7b09914