TOPICAL REVIEW

Recent progress in 2D metal-organic framework photocatalysts: synthesis, photocatalytic mechanism and applications

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Abstract

2D metal-organic framework (2D MOF) nanosheets and their derived nanocomposites have been widely studied in recent years due to their ultrathin atomic-level thickness, large surface area and adjustable structure. This review is thus aimed at summarizing the recent studies on synthesis methods and the photocatalytic mechanism of 2D MOF nanosheets. The synthesis methods can be concretely divided into top-down and bottom-up methods, including physical and chemical exfoliation, interfacial synthesis, three-layer synthesis and surfactant-assisted synthesis. The photocatalytic mechanisms can also be categorized into three classes: photo-absorption, photo-generated carrier separation and transport, and surface redox reaction. Moreover, the applications of 2D MOF nanosheets in the field of photocatalysis, including photocatalytic hydrogen evolution, photocatalytic CO$_2$ reduction, photocatalytic degradation and organic chemical photosynthesis, were also briefly discussed. Finally, some challenges and expectations with regard to 2D MOF nanosheets in photocatalysis will be addressed.

1. Introduction

Recent rapid developments in the economy together with population expansion have increased the human demand for energy. The use of traditional fossil fuels will lead to environmental pollution (e.g. air and water pollution, and the greenhouse effect) [1, 2], highlighting the need for a novel clean and sustainable energy conversion technology. As an ideal renewable and clean source of energy [3, 4], the sun can inexhaustibly supply the energy demand for billions of years.

Photocatalysis refers to the transformation of solar energy into chemical energy. Photocatalytic hydrogen evolution, photocatalytic CO$_2$ reduction and photosynthesis of small organic molecules are some examples of photocatalysis [5–13]. Furthermore, photocatalysis can degrade organic pollutants and reduce heavy metal ions in wastewater [14, 15]. With regard to the promising potential of photocatalysis in energy and environmental protection, the development of an efficient photocatalyst is crucial.

Metal-organic frameworks (MOFs) are porous architectures of a periodic network formed by the self-assembly of metal ions and organic ligands [16, 17]. In 1999, Yaghi and co-workers reported the famous MOF-5 with a specific surface area up to 2900 m$^2$ g$^{-1}$, which exhibited good gas adsorption capacity [18]. Since then, MOF has ushered in the golden age [19–26]. Today, MOFs are widely applied in gas separation and storage, electrocatalysis, photocatalysis, magnetism, fluorescence, sensing and drug transportation due to their large specific surface area, adjustable pore structure and functional tunability [27–48]. However, bulk MOFs also have some disadvantages, such as low metal utilization as well as poor ion diffusion ability. Since the discovery of graphene in 2004, 2D materials have quickly attracted attention due to their unique electronic structure and ultrathin morphology, such as boron nitride, metal dichalcogenides, MXene, as well as 2D MOFs, etc. 2D MOF not only refers to the ultrathin 2D morphology but to the high aspect ratio with a small thickness and large lateral area, which are typical of 2D materials. 2D MOFs can effectively enhance the

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adhesive force and contact area between the surface and substrate by forming films on surfaces, which are more beneficial for light absorption. 2D MOFs with defects and co-ordinatively unsaturated positions are similar to semiconductor materials in the photocatalytic process. Hence, it is of great importance that 2D MOFs are quickly and efficiently prepared from bulk MOFs. In recent years, about 1506 papers in the literature related to 2D MOF nanosheets have been reported, mainly focusing on synthesis methods as well as applications, which manifest that 2D MOFs are at a stage of rapid development (figure 1). Herein, it is necessary to make a systematic review focusing on the synthesis methods and photocatalytic applications of 2D MOFs.

In this review, the related contents are divided into four parts. The first part is devoted to an overview of the synthesis and preparation of 2D MOF nanosheets, including top-down and bottom-up methods. The second part briefly addresses possible photocatalytic mechanisms. Various photocatalytic applications of 2D MOF nanosheets, such as photocatalytic hydrogen generation, photocatalytic CO₂ reduction, etc, will be briefly discussed in part three. Finally, the challenges and future research opportunities of 2D MOF nanosheets will be expressed.

2. Synthesis of 2D MOF nanosheet methods

Numerous methods have been recently applied for synthesizing 2D MOF nanosheets, among which sonication and mechanical exfoliation [49, 50], chemical exfoliation [51], interfacial synthesis [52], three-layer synthesis [49], and surfactant-assisted synthesis [53] can be mentioned. These methods can be classified into two general categories: top-down and bottom-up methods, which will be introduced and discussed in detail.

2.1. Top-down methods

The top-down method refers to taking advantage of physical or chemical methods to exfoliate the layered-structure MOF from the bulk MOF. Layered MOFs have strong intra-layer coordination bonds and weak interlaminar Π-Π interactions, van der Waals forces or hydrogen bonds [53, 54]. Therefore, we can easily apply an external force to destroy the weak II-Π interactions, van der Waals forces or hydrogen bonds to obtain ultrathin 2D-MOF nanosheets.

2.1.1. Physical exfoliation

Physical exfoliation involves the application of an external physical force (through sonication, wet ball milling and freeze-thaw) to destroy the weak interlayer interactions and obtain 2D-MOF nanosheets [55, 56]. The exfoliation efficiency of the physical methods is largely related to the use of the solvent as the stripping efficiency greatly varies with different solvents. Common solvents are methanol, ethanol, water, acetone and tetrahydrofuran. Sonication exfoliation has been extensively employed in diverse solvents to obtain 2D-MOF nanosheets. For example, in 2011, Cheetam and co-workers reported new ultrathin Mn-DMS (DMS = 2,2-dimethyl succinate) nanosheets via sonication exfoliation to break the weak interlayer interaction, in which the thickness of the nanosheets varied between 1–10 nm (figure 2(a)). They explored various solvents such as water, methanol and ethanol hexane to exfoliate the bulk MOF, where ethanol exhibited the most efficient exfoliation [50]. In 2014, Yang’s group combined sonication and wet ball-milling to synthesize ultrathin Zn₂(bim)₄ molecular sieve nanosheets (Zn₂(bim)₄ MSNs) [57]. As shown in figure 2(b), the bulk Zn₂(bim)₄ MOF displayed weak van der Waals forces. Therefore, they adopted wet
ball-milling with a methanol and propanol solvent at 60 rpm for 1 h and then ultrasonic treatment to obtain the ultrathin Zn₂(bim)₄ MSNs. Zhao et al developed a freeze-thaw exfoliation technology to obtain MOF nanosheets [58]. As displayed in figure 2(c), they dispersed the MOF crystal in hexane followed by complete freeze-drying in liquid nitrogen and thawing in a hot water bath. The shear force caused by the change of solid and liquid volume resulted in the peeling of the bulk MOF crystal.

2.1.2. Chemical exfoliation
Compared with physical methods, chemical methods can offer a higher yield. Chemical methods involve the decomposition or structural modification of the pillar ligand in MOF crystal, such as intercalation and chemical exfoliation. As illustrated in figure 2(d), Zhou et al first introduced 4,4′-dipyridyl disulfide into the bulk layer Zn₂(PdTCP) MOF to enlarge the interlayer distances [51]. Then, trimethyl phosphorus was used to destroy the disulfide bond and peel off the bulk MOF crystals. The thickness of the nanosheets was controlled by adjusting the amount and reaction time of trimethyl phosphorus to give rise to a high yield (57%).

All in all, the top-down methods can be regarded as a facile approach for synthesizing 2D-MOF nanosheets from layered pristine MOF [59]. However, this method also suffers from some disadvantages. The products obtained by top-down methods have low uniformity and instability, are easily restacked and have low yield, which limits their large-scale production [60, 61].

2.2. Bottom-up methods
The bottom-up methods are based on crystal growth and directly synthesize wafer crystals from organic ligands and metals under specific conditions, implying a limitation on their vertical growth while promoting their horizontal growth [62]. More importantly, the bottom-up methods can synthesize the uniform thickness of non-layered MOF nanosheets at high yields. Three synthesis methods, including interfacial synthesis, three-layer synthesis and surfactant-assisted synthesis methods will be discussed.

2.2.1. Interfacial synthesis method
The interface refers to the site of reaction between organic ligands and metal ions. The interfacial synthesis method can be categorized into liquid/liquid interface and gas/liquid interface [63, 64]. Therefore, 2D-MOF nanosheets only grow in the confined interface regions.
In the gas/liquid interfacial synthesis, the surface of the liquid is covered with a small organic solvent with dissolved metal ions and organic ligands. By evaporation of the organic solvent, a gas/liquid interface is formed, giving rise to ultrathin MOF nanosheets. This method has been widely exploited to synthesize MOF nanosheets \[63, 65\]. As depicted in figure 3(a), Nishihara and co-workers dropped a small amount of ethyl acetate solvent containing benzenehexathiol ligand onto the surface of nickel acetate aqueous solution \[52\]. Thin nanosheets (thickness: 0.6 nm) were formed at the gas/liquid interface upon the slow evaporation of ethyl acetate.

In the liquid/liquid interfacial synthesis, two immiscible liquids are used to dissolve the organic ligands and metal ions, such as water/dichloromethane and water/ethyl acetate, where the ultrathin MOF nanosheets were generated at this liquid/liquid interface \[66–74\]. As shown in figure 3(b), Nishihara and co-workers also reported that the benzenehexathiol ligand reacted with nickel acetate at the water-CH\(_2\)Cl\(_2\) interface to generate ultrathin nanosheets with 1–2 \(\mu\)m thickness \[52\]. In the liquid/liquid interfacial synthesis method, the thickness of the synthesized 2D-MOF nanosheets can be controlled by adjusting the concentration of the ligands and metal ions. However, the thickness of the 2D-MOF nanosheets often exceeds 100 nm. Therefore, gas/liquid interfacial methods are used to synthesize thinner or single-layer MOF nanosheets in preference to liquid/liquid interfacial methods.

Interfacial synthesis is a facile and common method for the synthesis of 2D-MOF nanosheets. However, this method also has some drawbacks. The interfacial synthesis methods are only suitable for MOF crystals grown at room temperature. Moreover, the growth of the interfacial region may limit the yield of MOF. As a consequence, this method is not suitable for the large-scale synthesis of 2D-MOF nanosheets.

2.2.2. Three-layer synthesis method

The three-layer synthesis method has been widely utilized to synthesize MOF crystals by delaying the diffusion rate and crystal growth rate. As its name implies, the three-layer solvent method employs two miscible solvents with quite different densities where the lower-density solvent lies on top of the higher-density one and a buffer zone applies these two mixed solutions \[75–77\]. Recently, Gascon \textit{et al} applied the three-layer method to synthesize ultrathin Cu-based MOF nanosheets (Cu-BDC NSs) \[49\]. As shown in figure 4, 2 ml of DMF and 1 ml of CH\(_3\)CN containing organic ligands were used as the bottom layer, while 1 ml of DMF and 2 ml of Cu ion-dissolved CH\(_3\)CN were employed as the top layer. At the same time, the 2 ml of DMF and 1 ml of CH\(_3\)CN served as a buffer solution to slow down the diffusion rates of metal ions and organic ligands, where the ultrathin Cu-BDC NSs were generated at the middle buffer solution.
2.2.3. Surfactant-assisted synthesis method

The surfactant-assisted synthesis method involves the use of polyvinylpyrrolidone (PVP) surfactant [78, 79]. It is known that in synthesis nanomaterial progress, the incorporation of PVP surfactant can regulate and control the specific morphology and structure. In 2015, Zhang’s group developed two methods to synthesize Zn-based MOF (Zn-TCPP) [80]. 2D Zn-TCPP nanosheets were synthesized by using the surfactant-assisted method while bulk Zn-TCPP was prepared by using a traditional synthesis technique (figure 5). PVP surfactant played two leading roles in this experiment. First, it was selectively absorbed on the surface of the layer-structure MOF and restricted its longitudinal growth, thus forming ultrathin nanosheets. Second, the PVP surfactant prevented the 2D nanosheets from restacking onto the bulk MOF.

In summary, the bottom-up methods have been widely applied for the preparation of MOF nanosheets [81–85]. This method can control the thickness of the products by reaction conditions and results in high yield. However, their crystal dynamics and self-assembly mechanisms are still unclear and should be further elucidated. Currently, the development of a universal strategy for the larger-scale production of MOF nanosheets remains a challenge.

3. Photocatalytic mechanism

In recent years, the scientific community has taken a strong interest in the field of photocatalysis [86–91]. Some key issues, such as poor photoconversion, low product selectivity and low charge transfer/separation efficiency, still remain unresolved [92–94]. In this regard, a deeper understanding of the basic photocatalytic mechanism could be helpful. The photocatalytic process is divided into three main parts: photo-absorption, photo-generated carrier separation and transport, and reduction or oxidation reactions on the surface [95, 96]. (figure 6) Photo-absorption is the premise of the whole photocatalytic process, which requires the material to have a wide photo-absorption range from UV to visible. When the light energy is larger than the band gap of the material (\( h \nu \geq E_g \)), the material can efficiently absorb most photons in the solar spectrum. MOF can be used as a semiconductor material due to the aromatic organic linker ligand or metal ion/metal oxide clusters. The aromatic carboxylic acid ligand exhibits an intense UV absorption peak near 250 nm due to the excess electron density. A feasible strategy is to design a suitable band gap by changing the functional groups on the aromatic ligands, such as –NH₂, introducing some dye chromophores (porphyrins, BODIPY)
or regulating metal ion/metal oxide clusters. Hence, many researchers have changed the photo-absorption range through designing Ti–O cluster MOF or constructing MOF and TiO$_2$/BODIPY composite materials. Subsequently, at light excitation, MOF gives rise to the process of photo-generated carrier separation and diffusion on the catalyst surface due to the tight binding and rigid conjugation of organic ligands and metal nodes, which transfer electrons from the ligand to the metal nodes. However, this process can be halted because of their easy recombination due to their directionless transfer, which is not conducive to photocatalysis. Thus, researchers have reduced the thickness of the MOF material to an atomic scale to suppress the electron–hole recombination and accelerate charge transformation, which combines the advantages of 2D materials with MOFs in photocatalysis. Finally, the photogenerated electrons and holes on the surface of MOF reduce or oxidize the adsorbed species to generate different products, which can be divided into photocatalytic hydrogen evolution, photocatalytic CO$_2$ reduction, photocatalytic degradation and photosynthetic organic chemicals. In this step, the photocatalytic activity mainly depends on the oxidation-reduction potential of the conduction band and valence band, respectively. The more positive the oxidation-reduction potential of the valence band is and the more negative the oxidation-reduction potential of the conduction band is, the stronger the oxidation and reduction ability of the photogenerated electrons and holes will be. The photocatalytic activity is inefficient due to the limited light absorption efficiency or photogenerated electron–hole recombination. Hence, the photocatalytic system often introduces active...
sites/co-catalysts, such as Pt, which play a key role in determining different catalytic performances. 2D MOF as a photocatalyst has great advantages, but in practical application it is often difficult for a single 2D MOF to obtain excellent catalytic performance. Thus, it is necessary to introduce some co-catalysts. Therefore, it is a feasible idea to construct heterojunction composites with 2D- MOF nanosheets and other materials.

In the next section, we will briefly study and explore the application of photocatalysts in four fields, including photocatalytic hydrogen evolution, photocatalytic CO\(_2\) reduction, photocatalytic degradation and photosynthetic organic chemicals.

4. Photocatalytic applications

MOFs have been extensively applied in the field of photocatalysis due to their outstanding features, such as high porosity, high specific surface area, adjustable structure and facile preparation from various metal/metal oxide/carbon composite materials [97–99]. 2D MOF nanosheets have the advantages of 2D materials and MOFs, which are extensively applied in the fields of electrowaterysis and photocatalysis [61, 100, 101]. Here, we briefly introduce the applications of 2D MOFs in photocatalysis, including photocatalytic hydrogen evolution, photocatalytic CO\(_2\) reduction, photocatalytic degradation and photosynthetic organic chemicals.

4.1. Photocatalytic hydrogen evolution

Hydrogen is a promising new clean energy in the 21st century. Solar-driven photocatalytic hydrogen generation is one of the hot research directions at present, which can solve the energy crisis and environmental pollution problem. However, there are some core difficulties with photocatalysts, such as high cost, instability as well as low efficiency. In 2010, Silva's group first reported the direct usage of two kinds of Zr-MOFs as photocatalysts for hydrogen generation [102]. They synthesized the Zr-MOFs formed by terephthalate (UiO-66) and 2-aminoterephthalate ligands (UiO-66-NH\(_2\)) to serve as semiconductors for hydrogen evolution. Nonetheless, the H\(_2\) generation rate was low (248 and 372 umol h\(^{-1}\) g\(^{-1}\) for UiO-66 and UiO-66-NH\(_2\)). Hence, it is vital to explore cheap, efficient and stable photocatalysts. Since then, scientists have intensively researched photocatalytic hydrogen generation [103–107]. It was found that the efficiency of hydrogen generation could be drastically improved by the introduction of Pt into MOF as a co-catalyst and the regulation of Pt content or the catalysts with active sites for HER to replace Pt as a co-catalyst [108, 109]. However, the application of 2D MOFs in photocatalytic hydrogen evolution has rarely been reported. As shown in figure 7, Qiao et al synthesized a series of CdS nanoparticle-loaded ultrathin 2D \([\text{Ni(phen)(oba)}]_n0.5\text{H}_2\text{O}\) nanosheets (CdS/2D NMF NSs) by changing the number of NMF NSs. When mixing 50 mg of CdS with 2.5 ml of 2D NMF NS ethanol solution, the obtained sample was named the 2.5 NC sample, which showed excellent hydrogen generation rates (45201 umol h\(^{-1}\) g\(^{-1}\)), outperforming the Pt-loaded CdS [110]. Experiments and DFT calculations demonstrated that the interactive characteristics between 2D MOF and CdS synergistically contribute to the excellent photocatalytic activity. This work provided a feasible strategy to design 2D MOF nanosheet heterojunction photocatalysts without noble metal co-catalysts.

4.2. Photocatalytic CO\(_2\) reduction

With rapid energy consumption and consequent serious environmental pollution, it is of great significance for photocatalytic CO\(_2\) reduction to transform CO\(_2\) into organic raw materials and fuel through artificial photosynthesis. Photocatalytic CO\(_2\) reduction involves a multi-step electron transfer process and different electron transfer numbers corresponding to different reduction products, such as CO, HCOOH, CH\(_3\)OH and HCHO [112]. Halmann and co-workers first used GaP as a photocatalyst to reduce CO\(_2\) to HCOOH [113]. Since then, studies in this promising field have boomed [114–118]. For example, Zhang et al adopted a facile method to synthesize ultrathin 2D porous Co\(_3\)O\(_4\) photocatalyst by the pyrolysis of 2D-MOF nanosheets, which could be applied in efficient photocatalytic CO\(_2\) reduction utilizing Ru-based photosensitizer [119]. The CO generation rate was approximately 4.52 umol h\(^{-1}\) with a selectivity of 70.1%, superior to that of the bulk Co\(_3\)O\(_4\). In 2019, Liu's research group synthesized novel 0D carbon nitride quantum dots (CNQDs) with ultrathin 2D porphyrin MOF (g-CNQD/PMOF hybrids). The detailed synthesis steps are illustrated in figure 8(a) [111]. They found that g-CNQDs were coordinated with Co atoms of PMOF, leading to electron–hole pair separation and long-lived trapped electrons in Co atoms to enhance photocatalytic CO\(_2\) reduction into CH\(_4\). The g-CNQD/PMOF hybrid exhibited CO and CH\(_4\) generation rates of 16.10 and 6.86 µmol g\(^{-1}\) h\(^{-1}\), respectively. This strategy is expected to be applied in the design of efficient light absorption and fast mass transfer.

In conclusion, the application of 2D-MOF-based materials in photocatalytic CO\(_2\) reduction is still in its early stages, as several challenges remain unresolved.
4.3. Photocatalytic degradation

The rapid development of social production leads to an endless stream of harmful pollutants, such as formaldehyde, benzene, dioxin, dyes as well as pesticide, etc, which pollute the living environment and harm human health. Therefore, it is vital to explore efficient technologies to remove pollutants from industrial and domestic wastewater or waste gas. Photocatalytic degradation can be simply described as two key steps: (a) under light radiation, the catalyst captures photons and generates electron–hole pairs; (b) whereafter, they migrate to some molecules (H₂O, O₂, OH⁻) adsorbed on the surface of the catalyst to form active free...
Figure 9. (a) Synthesis steps of Ni-MOF/NF. (b) Produced intermediates of the photocatalytic oxidation of ethyl acetate by Ni-MOF/NF. Reproduced from [126] with permission of The Royal Society of Chemistry.

radicals (\(\cdot \text{O}_2^-\), \(\cdot \text{OH}\)) for degradation reaction. The application of MOF catalysts in the photocatalytic degradation of organic pollutants has aroused attention due to their high surface area and low cost [120–124]. In 2016, Han et al prepared BiOBr/NH\(_2\)-MIL-125(Ti) composite for the photocatalytic degradation of rhodamine B [125]. They proved that the enhanced photocatalytic performance may be due to the intervalence electron transfer between Ti\(^{3+}\) and Ti\(^{4+}\) and the synergistic effect between NH\(_2\)-MIL-125(Ti) and BiOBr, leading to the separation of photogenerated electron–hole pairs in the photodegradation process. However, the bulk MOFs have a limited light absorption range and a certain number of active centers. Hence, designing 2D MOFs with more exposed active sites and fast mass/electron transfer to optimize photocatalytic degradation performance is of great importance. As shown in figure 9, Zhao’s group in situ synthesized well-aligned Ni-MOF nanosheets on nickel foam (Ni-MOF/NF), which could effectively photocatalytically degrade ethyl acetate. They reported that Ni-MOF/NF has the advantages of Ni-MOF nanosheets and nickel foam with highly exposed active sites, light-harvesting centers and fast mass and electronic transport channels, which synergistically photocatalytically degrade ethyl acetate into CO\(_2\) and H\(_2\)O [126]. This work provides a feasible design idea for the photocatalytic degradation of pollutants by loading some 2D-MOF nanosheets onto a nickel foam substrate.

4.4. Organic chemical photosynthesis

Traditional organic synthesis reactions require some dangerous reagents or react at high temperature and pressure conditions, and the product selectivity is poor. Therefore, researchers are devoted to developing a mild, safe and environmentally friendly catalyst with low energy consumption. While the photocatalytic synthesis of organic chemicals meets the requirement of researchers due to their demonstrated advantages: (a) solar energy is an inexhaustible energy source, reducing traditional energy consumption; (b) the conditions of the photocatalytic reaction are mild; (c) it can selectively synthesize target products and improve the yield; (d) some photocatalysts can be recycled for reactions. Hence, taking the place of traditional organic reactions, the photocatalytic synthesis of conventional chemicals has aroused significant interest. However, the application of 2D-MOF nanosheets in the photocatalytic synthesis of organic chemicals has rarely been reported to date [127, 128]. In 2019, Zhou et al emphasized that
photonsensitizer-anchored 2D PCN-134 MOF nanosheets (PCN-134-2D) possessed more stability and tunability, and thus could be used for the photosynthesis of $^{1}$\textsuperscript{O}_2 and artemisinin [129]. Compared with the bulk PCN-134 MOF (PCN-134-3D), PCN-134-2D exhibited an excellent yield of artemisinin, outperforming all reported homo- or heterogeneous photosynthesis artemisinin products (figure 10). This enhancement could be due to the incremental substrate diffusion and catalyst accessibility. From this work, we can design various 2D-MOF photocatalysts by regulating and controlling the structure to modify functions.

5. Conclusion and outlook

In conclusion, it is necessary to make a systematic summary of the 2D MOF and its applications in photocatalysis. Based on the above findings, this review presents a detailed summary of the synthesis of 2D-MOF nanosheets by top-down and bottom-up synthesis methods. Then, the possible mechanisms of photocatalysis were surveyed and they can be divided into three parts: photo-absorption, photo-generated carrier separation and transport, and surface redox reaction. Finally, the photocatalytic application of 2D-MOF nanosheets was briefly described in photocatalytic hydrogen generation, photocatalytic CO$_2$ reduction, photocatalytic degradation and organic chemical photosynthesis.

Still, some core issues of 2D-MOF photocatalyst need to be resolved. The first challenge is the development of a universal and high-yield synthesis method for the large-scale preparation of 2D-MOF photocatalysts. Second, the overall efficiency of photocatalysis should be enhanced. Based on the photocatalytic mechanisms, three parameters can affect the overall efficiency: photo-absorption, transport and separation of photogenic carriers, and surface oxidation or reduction reaction. Improvements in any of these parameters can result in the design and synthesis of novel photocatalysts with increased efficiency. Apart from these prominent issues, some basic research on the application of 2D-MOF photocatalysts should be encouraged, such as the enhancement of photocatalytic stability and the application of photocatalytic tandem reaction. Finally, the structure–activity relationship of photocatalytic materials and the study of photocatalytic mechanism are still unclear. Hence, some advanced characterization techniques are needed for further study, such as synchrotron radiation, neutron diffraction, in situ TEM, etc. As a consequence, we are looking forward to witnessing the development of catalysts with facile industrial-scale production or the regulation and control of the semiconductor properties of 2D-MOF nanosheets to offer a wider range of photo-absorption and stronger separation ability of photogeneration carriers or the introduction of catalysts with efficient catalytic sites into 2D-MOF nanosheet semiconductor materials. In general, the photocatalytic usage of 2D-MOF nanosheets still requires much research, and numerous challenges are waiting to be resolved in the future.
Data availability statement

No new data were created or analyzed in this study.

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Conflicts of interest

The authors declare no conflict of interest.

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