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From Waste to Resource: Upcycling PET into High-Performance MOFs for Advanced Applications

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Due to the non-degradable nature of polyethylene terephthalate (PET) and the widespread use in food packaging, clothing, and other fields of PET, discarded PET waste continues to accumulate globally, posing significant risks to both the environment and human health. Through chemical recycling methods, PET waste can be decomposed into terephthalic acid (TPA), which serves as an organic linker of metal-organic frameworks (MOFs) and demonstrates potential for achieving PET waste upcycling, thus garnering considerable attention. MOFs prepared from PET waste have been extensively applied in fields such as adsorption, catalysis, and energy storage. This review aims to analyze the latest research advancements concerning the MOFs prepared from PET waste to provide insights for further development in both the preparation and application of MOFs prepared from PET waste. The comprehensive analysis of this review highlights the innovative pathways toward addressing environmental challenges while enhancing the utility of recycled resources.

Keywords: PET waste, MOFs, upcycling, preparation, application.

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INTRODUCTION

With the development of the economy, polymer materials have replaced traditional materials such as metals and wood, finding widespread applications in fields like electronics and electrical appliances, packaging, and transportation[1–3]. PET, a widely utilized polymer material that is renowned for its non-toxicity, excellent heat resistance, high mechanical strength, and superior chemical stability, is the preferred choice for applications in food packaging and household products[4]. However, the extensive use of PET products has led to the generation of massive amounts of PET waste. Currently, approximately 70 million tons of PET plastic are produced globally each year, accounting for 12% of global solid waste[5]. Due to the structural stability of PET, discarded PET waste exhibits significant resistance to natural degradation, leading to substantial accumulation in landfills or direct environmental dumping, thereby causing severe pollution. Although PET waste can be recycled, most countries achieve recycling rates below 30%, primarily due to high recycling costs and low economic returns[6]. Consequently, transforming PET waste into a process that yields high-value-added products while enhancing the economic viability of waste PET has become an urgent challenge to address. Over the past decade, research on PET waste has gained increasing attention[7]. According to data from the Web of Science database, the number of published research papers on PET waste has shown a steady annual increase, rising from over 170 papers in 2014 to more than 1,800 papers in 2024 (Figure 1). Strengthening research on PET waste recycling is therefore critical for improving PET waste management, enabling sustainable resource utilization, and advancing environmental protection efforts.

The recycling methods for PET waste primarily include mechanical recycling and chemical recycling[8]. Mechanical recycling involves the processing of PET waste into new products through steps such as mechanical shredding,

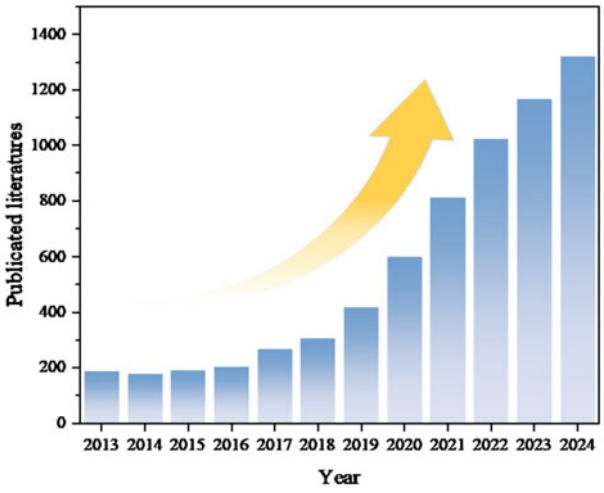

Figure 1. Recent publications on PET waste

melting, and remolding, which allows for the large-scale production of PET products from waste within a short timeframe[9]. However, several challenges are associated with mechanical recycling. The first problem is impurity removal. PET waste must be subjected to rigorous cleaning to eliminate contaminants (e.g., labels, adhesives), which increases the complexity of the recycling process. The second problem is PET decomposition. Repeated mechanical recycling results in the decomposition of PET, leading to a significant decline in mechanical properties over multiple cycles. The third problem is food safety limitations. Products manufactured through mechanical recycling are generally unsuitable for food packaging applications due to potential contamination risks, restricting their use in this critical sector. Chemical recycling, on the other hand, is regarded as the most promising approach for PET waste recovery[10]. Chemical recycling employs chemical reactions to break down PET waste into organic compounds such as terephthalic acid (TPA), dimethyl terephthalate, ethylene glycol, and

para-xylene. The resulting monomers and intermediates can be repurposed as high-quality raw materials in the petrochemical industry or utilized to synthesize advanced materials, offering broad application prospects. Chemical recycling not only addresses the limitations of mechanical methods but also aligns with circular economy goals by enabling the production of virgin-grade PET suitable for food-contact applications[11]. Therefore, chemical recycling holds greater potential for transforming PET waste into high-value materials and closing the loop in sustainable resource utilization.

MOFs are formed through the ordered assembly of organic ligands and metal ion connectors via coordination bonds, with over 10,000 distinct MOF structures reported to date[12]. Extensive research attention has been attracted to MOFs over the past decades due to their ordered pore structures, controllable morphology, high specific surface area, and abundant channel architectures. By now, promising applications of MOFs have been demonstrated in gas separation/adsorption, catalysis, supercapacitors, and controlled drug delivery systems[13]. Although MOFs possess numerous advantages, significant challenges such as low long-term stability and unsatisfactory cost-effectiveness remain to be addressed before the practical applications of MOFs can be fully realized[14]. With regard to long-term stability, chemical instability, limited thermal stability, and deteriorated performance during prolonged cycling are commonly observed in MOFs[15]. Some MOFs are prone to structural collapse or ligand dissociation when exposed to water or acidic/basic environments[16]. The structural degradation of MOFs may occur at temperatures exceeding 200 °C[17, 18]. During repeated application, a noticeable decline in performance of MOFs can be observed within tens to hundreds of hours. To address these issues, the development and application of MOFs with enhanced stability, including MIL-101, UiO-66, and MOF-74, have been proposed as effective strategies. In terms of cost--effectiveness, the utilization of MOFs is hindered by high production costs, complicated synthesis procedures, and difficulties in scaling up the production process. The large-scale synthesis of MOFs is currently confined to laboratory or pilot-scale studies, and a mature continuous manufacturing process has yet to be developed. To overcome these limitations, alternative solutions have been explored, including the use of low-cost raw materials for MOF synthesis to reduce overall production costs, the implementation of energy-saving techniques such as microwave-assisted or ultrasound-assisted methods, and the adoption of ball-milling processes to enhance the scalability of MOF fabrication for industrial applications. Efforts towards developing sustainable approaches for MOF preparation not only enhance economic viability but also promote broader adoption of MOFs across various industries.

PET is composed of approximately 85% TPA monomers, which is utilized as a key ligand in the synthesis of MOFs such as MIL-88B, MIL-47(V), UiO-66, MIL-53, and MIL-101[19, 20]. The use of PET waste as a feedstock for MOF production provides dual advantages. First, economic and environmental benefits are achieved by reducing production costs and environmental impacts through the recycling of PET waste resources. Second, resource circularity is enabled by effectively recycling resources, aligning with sustainable development goals. These advancements have established PET waste-derived MOFs as a prominent research focus, offering innovative pathways for both upcycling of PET waste and scalable industrialization of MOFs. To promote the development of MOFs and the utilization of PET waste, recent work on the preparation and application of PET waste-derived MOFs has been analyzed in this work. Additionally, the opportunities and challenges encountered in the application and preparation of PET waste-derived MOFs have been discussed.

METHODS FOR PREPARING PET WASTE-DERIVED MOFS

At present, the preparation of MOFs using PET waste typically involves several steps: pretreatment, depolymerization, metal coordination, and post-treatment[21]. Based

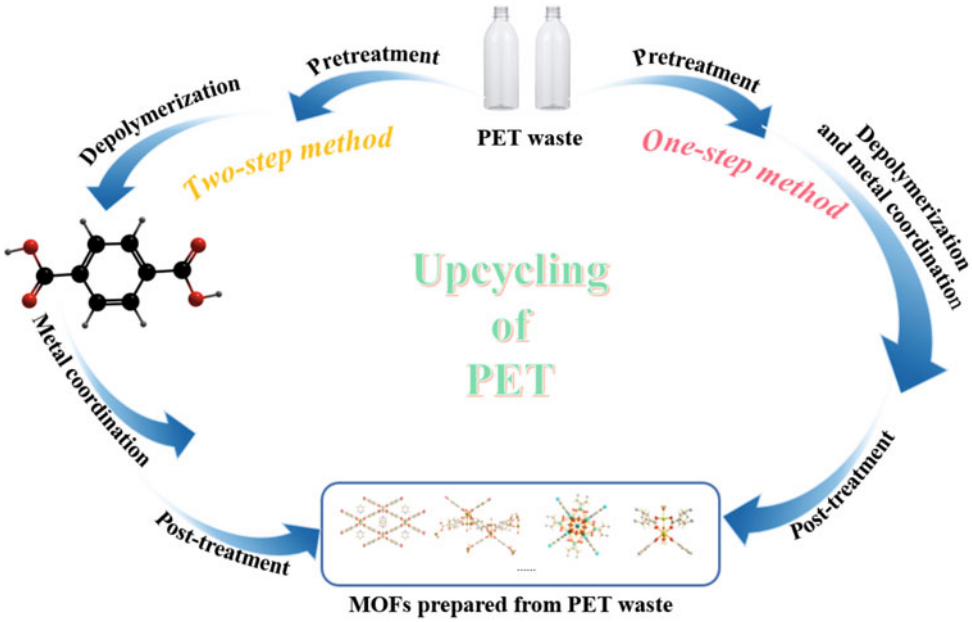

Figure 2. Methods for preparing PET waste-derived MOFs

on differences in the implementation of depolymerization and metal coordination, the methods for preparing MOFs using PET waste are classified into one-step method and two-step method (Figure 2). In the one-step method, PET waste is depolymerized into its basic components, including TPA and ethylene glycol. TPA is directly reacted with metal salts within the reaction system for the synthesis of MOFs. Throughout the entire process, the separation and purification of TPA are not required. In the two-step method, PET waste is first depolymerized into monomers such as TPA through decomposition reactions like hydrolysis. Subsequently, the purified TPA is utilized as an organic ligand and undergoes a hydrothermal reaction with metal salts under high temperature and pressure conditions to synthesize MOFs.

One-step method

In the process of implementing the one-step method, the method can be further divided into hydrothermal, solvothermal, microwave-assisted, and mechanochemical methods based on different implementation paths[22–36]. Tables 1 to 4 summarize recent studies on the preparation of MOFs via the one-step method. It should be noted that the preparation process of MOFs, in which pure TPA is not obtained, is classified as the one-step method.

The hydrothermal method involves utilizing water as the reaction medium, where PET waste is degraded and coordinated with metal ions simultaneously under high temperature conditions in a high-pressure reactor to prepare MOFs[37]. By uniformly mixing PET waste with $CrCl_3 \cdot 6H_2O$ in deionized water, followed by an 8 h reaction in a hydrothermal reactor at 210 °C, octahedrally-shaped MIL-101(Cr) nanoparticles are synthesized[25]. MIL-101(Cr) is characterized by a specific surface area exceeding 3000 $m^2\ g^{-1}$. Additionally, the hydrothermal method is employed for the production of various other MOF materials, such as MIL-53 and MOF-5[24, 38].

To enhance PET waste decomposition and improve the quality of the prepared MOFs, the solvothermal method has been developed[28–32]. In this approach, organic solvents such as N, N-dimethylformamide (DMF) are used instead of water under high temperature and pressure conditions, facilitating PET waste decomposition for MOFs preparation. For the synthesis of Fe-MOF, PET waste, $FeCl_3 \cdot 6H_2O$, and acetic acid are first combined in DMF. The mixture is then transferred to a high-pressure reactor where a solvothermal reaction at 160 °C for 12 h is conducted, resulting in the final Fe-MOF[31]. Through this process, the conversion of PET waste into valuable Fe-MOF material is efficiently achieved, highlighting an effective approach for recycling PET waste. Both hydrothermal and solvothermal methods require the use of solvents and high-pressure reactors, leading to complex preparation processes and high energy consumption.

The mechanochemical method involves direct processing of PET waste and metal salts in a ball milling device, where mechanical forces enable PET decomposition and metal ion coordination at room temperature, effectively addressing the high energy consumption issues associated with hydrothermal and solvothermal methods. La-MOF, Zr-MOF, Ni-MOF, Co-MOF can all be prepared by mechanochemical method[33, 34].

Additionally, microwave-assisted synthesis can also be employed to reduce energy consumption by accelerating PET decomposition and metal ion coordination reactions through microwave heating[35, 36].

When using the one-step method for MOFs preparation, multiple substances coexist in the reaction system, including ethylene glycol produced from PET decomposition and metal salts required for MOFs synthesis. These substances may influence PET decomposition

Table 1. MOFs prepared from PET waste using the hydrothermal method

MOFs	Solvent/time (h)/temperature (°C)	BET surface area ($m^2\ g^{-1}$)	Morphology	Ref.
Fe/Al-MOF	water/72/220	–	–	22
Cr-MOF	water/8/210	3233	aggregates of nanoparticles	13
MOF-5(Zn)	ethanol/24/170	48	amorphous particles	24
MIL-101(Cr)	water/8/210	3055	aggregates of octahedron nanoparticles	25
MIL-101(Cr)	water/1/200	1809	aggregates of nanoparticles	26

Table 2. MOFs prepared from PET waste using the solvothermal method

MOFs	Solvent/time (h)/temperature (°C)	BET surface area ($m^2\ g^{-1}$)	Morphology	Ref.
Fe-MOF	DMF/12/160	128	spindle-like	27
Zr-MOF	DMF/12/160	290	irregular aggregates	27
La-MOF	DMF/12/160	62	irregular aggregates	27
UiO-66	formic acid and acetone/30/160	995	aggregates of hexagonal prism nanoparticles	28
MIL-53(Al)	DMF and water/12/180	–	rod-like crystals	29
Al-MOF	DMF and water/12/180	1606	aggregates of needle-like nanoparticles	30
Fe-MOF	DMF/12/160	169	aggregates of spindle-shaped particles	31
Mn,Co-MOF	DMF and water/15/180	–	aggregates of nanorod particles	32

Table 3. MOFs prepared from PET waste using the mechanochemical method

MOFs	Solvent/time (h)/temperature (°C)	BET surface area (m^2 g^{-1})	Morphology	Ref.
La-MOF	-/8/room temperature	29	rod-like nano particles	33
La-MOF	-/2/room temperature	143	irregular aggregates	34
Zr-MOF	-/2/room temperature	149	irregular aggregates	34
Ni-MOF	-/2/room temperature	46	irregular aggregates	34
Co-MOF	-/2/room temperature	46	irregular aggregates	34
Mn-MOF	-/2/room temperature	36	irregular aggregates	34
Ca-MOF	-/2/room temperature	18	irregular aggregates	34

Table 4. MOFs prepared from PET waste using the microwave-assisted method

MOFs	Solvent/time (h)/temperature (°C)	BET surface area (m^2 g^{-1})	Morphology	Ref.
La-MOF	DMF/1/160	77	–	35
Zr-MOF	DMF/1/160	294	–	35
UiO-66(Zr)	water and CH_3COOH /1/200	1206	aggregates of irregular cuboctahedron crystals	36

and MOFs crystal structures. Although some studies suggest that ethylene glycol has minimal impact on MOFs synthesis, its effect on MOFs morphology along with oligomers generated during PET decomposition remains unclear[39, 40]. Furthermore, metal salts can affect PET decomposition rates and the structure of TPA produced during decomposition. Reports indicate that metal chlorides can catalyze PET decomposition, while metal nitrates promote the formation of nitro terephthalic acid[41, 42]. These factors not only influence PET decomposition but also impact MOFs crystallization processes. Consequently, the one-step method represents a complex, multi-factor influenced process of MOFs formation and crystallization. Decomposition by-products and solvents significantly affect the structure of MOFs, making it challenging to produce stable and well-structured MOFs using the one-step method. Hydrothermal and solvothermal methods typically yield MOFs with relatively large specific surface areas but require long preparation time and solvents like DMF and acetone. Microwave-assisted method is effective in reducing preparation time. However, the amount of solvent required is not decreased. Mechanochemical method enables MOFs production at room temperature, yet the resulting materials often have small specific surface areas, usually less than 100 m^2 g^{-1}. Meanwhile, MOFs prepared using a one-step method are typically aggregates of nanoparticles with irregular shapes.

Two-step method

Two-step method involves the initial depolymerization of PET waste to obtain TPA, followed by purification. Subsequently, the purified TPA is reacted with metal salts to prepare MOFs. Two-step method facilitates not only the preparation of targeted MOFs but also the acquisition of high-purity TPA chemical raw materials. The primary distinction between the two-step and one-step methods lies in the fact that, in the two-step method, pure TPA is first obtained.

Depending on the method used to acquire TPA, two-step method can be categorized into chemical decomposition, mechanochemical, microwave-assisted, ultrasound-assisted, and enzyme-assisted methods[43–72]. Chemical decomposition is further divided based on the type of decomposition agent used, including hydrolysis, alcoholysis, aminolysis, and others[73]. During this process, water, ethylene glycol (EG), ethylenediamine, or other decomposition agents are added under the presence of acid or alkali catalysts, followed by high-temperature reactions to ultimately produce pure TPA. With the preparation of pure TPA, conventional MOFs synthesis processes can be employed during the MOFs production process. In these reactions, the main components consist of solvents, TPA, and metal salts, leading to relatively simple composition of reaction mixture and more controllable MOFs structures. Consequently, the two-step chemical decomposition method for preparing MOFs has been widely adopted. To mitigate issues associated with high energy consumption, environmental pollution, and complex handling arising from solvent and catalyst usage in chemical decomposition of PET, alternative methods such as mechanochemical processing, microwave-assisted decomposition, and biological methods can be utilized for PET waste decomposition. Tables 5 to 7 summarize recent studies on the preparation of MOFs using two-step methods.

It highlights the widespread application of chemical decomposition within the two-step process[43, 44]. Chemical decomposition method is the most widely used method. To produce TPA from PET waste, the PET waste is first ground into small pieces and then mixed with ethylene glycol and water, which undergoes reaction at 200 °C for 8 h. Following the reaction, the product is separated and washed to obtain TPA. Subsequently, the obtained TPA can be mixed with $CrCl_3 \cdot 6H_2O$ and acetic acid, which is subjected to another reaction at 210 °C for 8 h to synthesize MIL-101(Cr)[50]. The obtained MIL-101(Cr) exhibits an octahedral crystal morphology with BET surface area higher than 1500 m^2 g^{-1}. Through this process, PET waste is efficiently converted into valuable TPA and further into MOF materials, showcasing an effective recycling pathway.

The ultrasonic-assisted method can be employed during the degradation of PET waste into TPA or during

Table 5. MOFs prepared from PET waste using chemical decomposition method

MOFs	Solvent/time (h)/temperature (°C) during hydrolysis	Solvent/time (h)/temperature (°C)	BET surface area ($m^2\ g^{-1}$)	Morphology	Ref.
Cu-MOF	ethylene glycol/0.5/180	DMF/24/180	1321	cubic particles	43
Zr-MOF	ethylene glycol/0.5/180	DMF/24/180	720	irregular aggregates	43
Ti-MOF	ethylene glycol/0.5/180	DMF/8/80	574	irregular aggregates	43
MOF-5	ethanol/4/80	DMF/24/120	27	thick flat flakes	44
Ni/Co-MOF	ethylene glycol/4/180	DEF/24/100	813	aggregates of spherical particles	45
MIL-101(Cr)	water/10/100	water /12/220	1306	spherical-like particles and rod-like particles	46
MIL-101(Cr)	ethylene glycol/5/200	water /8/220	1964	aggregates of octahedral particles	47
MIL-101(Cr)	ethylene glycol and water/8/210	water /12/220	1922	ortho-octahedral particle	48
Ni-MOF	water/6/200	DEF/24/140	63	aggregation of 2D slices	49
UiO-66(Zr)	ethylene glycol and water/8/200	DMF/4/120	1215	cube-like shaped crystals	50
MIL-101(Cr)	ethylene glycol and water/8/200	water and acetic acid /8/210	1521	octahedral crystals	50
MIL-101(Fe)	ethylene glycol and water/8/200	DMF/20/110	2032	octahedron shaped-like crystals	50
Cu-MOF	ethylene glycol/0.6/180	DMF and ethanol/24/85	–	irregular nanoparticles	51
CoZn-MOF	ethanol and 1,4-dioxane/1/80	DMF and water/20/120	4	irregular particles	52
Ca-MOF	ethylene glycol/8/210	water and DMF/24/150	24	rod-like particles	53
CrNiFe-MOF	ethylene glycol /1/180	water /0.16/room temperature	22	hexagonal bipyramidal particles	54
Cu-MOF	ethylene glycol/8/210	DMF/12/150	–	rod-like particles	55
W-MOF	ethanol/4/200	DMF/2/30	–	hexagonal particles	56
Ag-MIL-101	ethylene glycol/0.5/170	water/12/30	–	irregular particles	57
Cu-Zn-MOF	ethylene glycol/0.5/170	DMF/36/110	–	cubic particles	58
UiO-66	water/24/180	water/24/120	1094	–	59
MOF-5	ethyl alcohol/4/200	DMF/7/100	1600	cubic-like particles	60
Ni-MOF	ethylene glycol and water /4/180	DEF/24/100	1523	cubic particles	61
MIL-53(Al)	NaOH/15/120	DMF/4/150	1202	elongated nanoparticles	62
MOF-5	ethylene glycol and water/8/210	DMF/24/120	535	cubic particles	63
MOF-5	ethylene glycol and water/5/180	DMF/ 24 /99	88	hexagonal nanoparticles	64
Zr-MOF	ethylene glycol and water/4/180	DMF/6/140	928	spherical nanoparticles	65
Tb-BDC	NaOH/24/180	water		flower-like particles	66
$Co_{0.8}$Ni-MOF	ethylene glycol and water/8/210	DMF,ethanol, water/24/150	14	dandelion-like particles	67
UiO-66	ethylene glycol and water/0.5/200	DMF acid/4/150	1139	aggregate of nanocuboids	68

Table 6. MOFs prepared from PET waste using ultrasonic-assisted method

MOFs	Solvent/time (h)/temperature (°C) during hydrolysis	Solvent/time (h)/temperature (°C)	BET surface area ($m^2\ g^{-1}$)	Morphology	Ref.
MIL-53(Fe)	Water/1.5 h/750 W	DMF/15/150	194	–	71
MIL-88B(Fe)	ethylene glycol and water/8/200	DMF/0.2/room temperature	1347	hexagonally bipyramidal shaped particles	50

the MOF synthesis process[71]. Using water as a solvent and a 750 W ultrasonic device, PET waste is degraded into TPA within 1.5 h. The resulting TPA can then be utilized to prepare MIL-53(Fe)[71]. Alternatively, PET waste is first chemically degraded into TPA, after which the TPA is reacted with iron salts under ultrasonic assistance, leading to the preparation of MIL-88B(Fe) in approximately 10 min[50].

Using mechanochemical method, Cu-MOF can be produced. Cu $(NO_3)_2 \cdot 3H_2O$ and TPA derived from PET waste are added to a ball mill. The mixture undergoes continuous reaction at 110 °C for 72 h, leading to the formation of Cu-MOF with the BET surface area higher than 700 $m^2\ g^{-169}$. Microwave-assisted method can be employed to reduce the time required for degrading PET waste into TPA. Using this method, PET waste can be degraded into TPA within 10 min, and the resulting TPA can be utilized for the preparation of MOF-5[70]. PETase is an enzyme capable of efficiently decomposing PET plastics by breaking the ester bonds in PET molecular chains, thus depolymerizing PET into TPA and EG. The enzyme-assisted PET decomposition method effectively reduces solvent usage and energy consumption during the PET decomposition process, positioning it as an innovative approach for PET recycling. Specifically, ThermoPETase can decompose PET waste into TPA under room temperature conditions within 48 h. The obtained TPA can then be used to prepare MOFs materials such as UiO-66[72].

Among the processes of preparing MOFs using the two-step method, MOFs materials prepared via the chemical decomposition method exhibit higher specific surface areas, typically exceeding 500 $m^2\ g^{-1}$, and possess well-defined morphologies compared to those produced by other methods. Moreover, chemical decomposition method does not require special equipment, making the method particularly advantageous for preparing MOFs using PET waste.

Applications of PET waste-derived MOFs

MOFs materials prepared from PET waste are observed not to differ significantly in microscopic structure from those synthesized through traditional methods, as both are formed by the assembly of organic ligands with metal ions/clusters into periodic network structures. To determine the structure of the TPA prepared from PET waste, the acid value, SEM morphology, XRD pattern, ^{1}H NMR spectrum, and FTIR spectrum of the TPA obtained from the degradation of PET waste were compared with those of commercially available

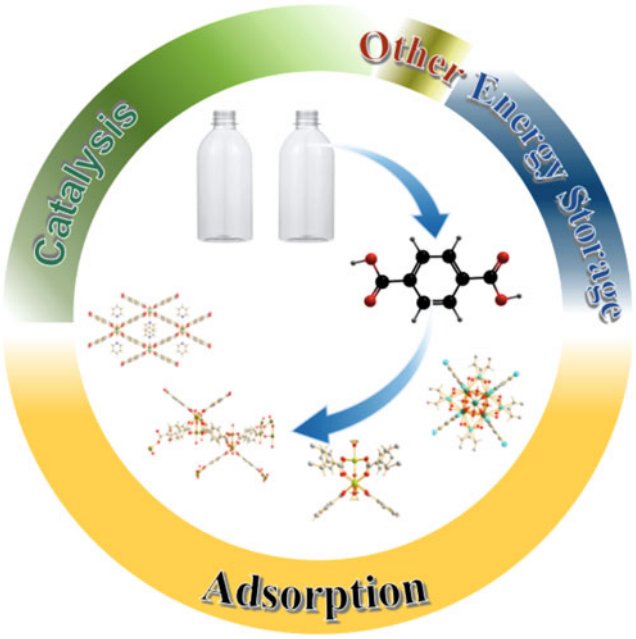

Figure 3. The application fields of MOFs prepared from PET waste

TPA[23, 49, 69, 74]. The analysis results revealed that the TPA derived from PET waste exhibits a high degree of structural consistency with the commercial TPA. However, differences in structure and performance are observed between MOFs prepared from PET waste and those prepared from commercial TPA. MOFs materials, C-MIL-101(Cr) and G-MIL-101(Cr)@R, were prepared by Keshta et al. using commercial TPA and PET waste as raw material, respectively[46]. A specific surface area of 2625.85 $m^2\ g^{-1}$ was achieved for C-MIL-101(Cr), whereas G-MIL-101(Cr)@R had a specific surface area of only 1305.84 $m^2\ g^{-1}$. When used for the adsorption of dye AB-92, C-MIL-101(Cr) exhibited an adsorption capacity of 3240 mg g^{-1}, while G-MIL-101(Cr)@R showed an adsorption capacity of 2176 mg g^{-1}. Heng et al. synthesized MIL-68(Al) and D-MIL-68(Al) from commercial TPA and PET waste, respectively[74]. Although the specific surface area of D-MIL-68(Al) was slightly lower than that of MIL-68(Al), D-MIL-68(Al) demonstrated a high adsorption capacity of 555.6 mg g^{-1} for dimetridazole, which is three times higher than the 181.8 mg g^{-1} capacity observed for MIL-68(Al). Commercial TPA and PET waste were utilized by Song et al. to prepare Ni–MOF–C and Ni–MOF–W[49]. The investigation results of XRD, XPS, and SEM revealed that both MOF materials exhibited similar structures. Both materials exhibited excellent catalytic activity in the photocatalytic

Table 7. MOFs prepared from PET waste using other methods

Methods	MOFs	Solvent/time (h)/temperature (°C) during hydrolysis	Solvent/time (h)/temperature (°C)	BET surface area ($m^2\ g^{-1}$)	Morphology	Ref.
Mechanochemical	Cu-MOF	water/24/125	-/72/110	726	aggregate of layered structure	69
Microwave-assisted	MOF 5	ethylene glycol/0.1/180W	DMF/2.5/room temperature	–	tetrahedral particles	70
Enzyme-assisted	UiO-66	-/40/48 (ThermoPETase enzyme)	DMF/24/120	417	octahedral particles	72

reduction of CO_2 to CO, with yields of approximately 10 mmol h^{-1} g^{-1}. Cr-MOF (BDC, Sigma-Aldrich) and Cr--MOF (BDC, PET-derived) were synthesized by Ren et al. from commercial TPA and PET waste, respectively[23]. The Cr-MOF (BDC, PET-derived) displayed a higher specific surface area (3233 m^2 g^{-1}) and enhanced hydrogen storage capacity (with H_2 uptake reaching 2.1 wt.%). Jindakaew et al. prepared MIL-53(Al) and PET-derived MIL-53(Al) using commercial TPA and PET waste, respectively[62]. Minimal differences were noted in XRD patterns, zeta potential, and BET surface areas between the two MOFs. For the adsorption of 2-phosphonobutane-1,2,4-tricarboxylic acid, MIL-53(Al) achieved an adsorption capacity of 793 mg g^{-1}, while PET-derived MIL-53(Al) reached 826 mg g^{-1}. Despite the structural and performance differences observed between MOFs prepared from PET waste and those synthesized from commercial TPA, these two categories of MOFs are found to possess comparable application potentials.

Since the organic ligand used in MOFs prepared from PET waste is noted to be exclusively TPA, the changes in ligand structure of the MOFs are limited. Despite this limitation, these MOFs are characterized by a high specific surface area, a high content of catalytically active metal centers, and abundant nanopores. Consequently, MOFs prepared from PET waste find wide application in fields such as adsorption, catalysis, energy storage, and etc. (Figure 3). The applications of MOFs prepared from PET waste, as published in recent years, are summarized in Table 8[74–78].

MOFs prepared from waste PET are regarded as highly efficient adsorption materials[46]. Owing to their high specific surface area and abundant pore size distribution, significant advantages in adsorption capacity and selectivity are exhibited, rendering them applicable in environmental remediation fields such as water purification, gas separation, and heavy metal ion capture. As a result, over 50% reported literatures about MOFs derived from PET waste are in the fields of adsorption and separation. Dye wastewater, produced by industries such as textiles, printing and dyeing, and paper production, when improperly treated, is allowed to enter water bodies, thereby posing threats to ecosystems and human health. Benzidine, generated during the decomposition of azo dyes, can be absorbed through the skin, potentially leading to anaphylactic shock or contact dermatitis. The growth of aquatic organisms is also inhibited by dye wastewater. MOFs derived from PET waste play a crucial role in mitigating the harmful effects of dye wastewater on both ecological systems and human health. As a porous material, various dyes, including acid blue 92 dye (AB-92), reactive red 2 (RR2), reactive blue 19 (RB19), methylene blue (MB), can be adsorbed by MOFs. The MIL-101(Cr) prepared from PET waste exhibited adsorption capacities of 663 mg g^{-1} and 864 mg g^{-1} for RR2 and RB19, respectively[48]. Antibiotics and drugs, when retained in the soil for extended periods, are known to disrupt microbial balance. When these substances are washed into water bodies by rain, they pose threats to aquatic organisms and drinking water safety. The prolonged intake of water or food containing drug residues is capable of damaging the nervous system and endocrine system, while also increasing cancer risk. Through the food chain, antibiotic and drug residues accumulate progressively, which can affect the normal physiological functions of birds, fish, and other organisms, potentially leading to population decline or ecological imbalance. MOFs derived from PET waste are acknowledged for their superior antibiotic and drug adsorption performance. Many antibiotics and drugs such as tetracycline and dimetridazole can be directly be adsorbed by MOFs derived from PET waste[63, 74]. The MOF-5 synthesized from PET waste, when applied to the adsorption of tetracycline, demonstrated a maximum adsorption capacity of 2325.55 mg g^{-1} according to the Langmuir isotherm model[63]. MOFs derived from PET waste can also be transformed into adsorbents for drug removal through methods such as compositing and carbonization. A carbon-metal oxide composite material (Al/Fe@MCC600) prepared from MIL-53(Al) exhibited removal efficiencies of 96.31%, 66.84%, 87.83%, and 90.07% for ibuprofen, diclofenac, naproxen, and ketoprofen, respectively[22]. MOFs derived from PET waste can also be used for the adsorption of other harmful substances, including arsenic-containing substances, fluorine-containing compounds, phosphorus-containing compound, cyclic organic molecules, metal ions, nano-particles (NPs), and etc. For example, Zr-MOF, Fe-MOF, and La-MOF, prepared from PET waste, exhibited arsenate adsorption capacities exceeding 70 mg g^{-127}. The perfluorooctanoic acid adsorption capacities of Zr-MOF and La-MOF exceed 290 mg g^{-135}. The 2-phosphonobutane-1,2,4,-tricarboxylic acid (PBTC) adsorption capacities of MIL-53(Al) exceeds 800 mg g^{-162}. The maximum adsorption capacities of Ca-MOF for lead ions, cadmium ions, and copper ions, as obtained from the Langmuir model, are 644 mg g^{-1}, 391 mg g^{-1}, and 260.5 mg g^{-1}, respectively[75]. In addition to their excellent adsorption capacity for these water-soluble harmful substances, MOFs prepared from PET waste also show a good adsorption ability to insoluble NPs. MOF-5 prepared from PET waste can be utilized to efficiently remove polyvinyl chloride (PVC) and polymethyl methacrylate (PMMA) NPs from water, with removal efficiencies reaching up to 97% and 95%, respectively[45]. MOFs prepared from PET waste are highly effective for the adsorption and separation of gases. When utilized for CO_2 capture, an adsorption capacity comparable to that of amine-based adsorbents is exhibited by MOFs, thereby contributing to the reduction of greenhouse gas emissions through carbon capture and storage[36, 60]. MOF-5 prepared from waste PET exhibited a CO_2 adsorption capacity of 7.8 mmol g^{-1} at a pressure of 1000 kPa[60]. In hydrogen storage at ambient temperatures, enhancements in the safety and economic viability of hydrogen energy utilization are achieved with the help of MOFs. Cr-MOF prepared from PET waste exhibits good hydrogen storage performance, with a hydrogen uptake reaching 2.1%[23]. The capability to adsorb water vapor of MOFs derived from PET waste is harnessed for humidity control in air or industrial drying processes, leading to optimized energy efficiency. UiO-66(Zr), MIL-101(Cr), MIL-101(Fe), and MIL-88B(Fe), prepared from PET waste, exhibit good water adsorption capabilities[50].

Catalysis stands out as another major application field for MOFs prepared from PET waste due to their

Table 8. Application of MOFs prepared from PET waste

Application field	Materials	Application purpose	Performance	Ref.
Adsorption	MIL-101(Cr)	adsorption of AB-92	adsorption capacity: 2176 mg g^{-1}	46
	MIL-101(Cr)	adsorption of RR2 and RB19	adsorption capacity of RR2 and RB19: 663 mg g^{-1} and 864 mg g^{-1}, respectively	48
	MIL-101(Cr)	adsorption of MB	adsorption capacity: 71 mg g^{-1}	25
	MIL-53(Al)	adsorption of MB	adsorption capacity: 12 mg g^{-1}	38
	MOF-5	adsorption of tetracycline	adsorption capacity: 2336 mg g^{-1}	63
	MIL-68(Al)	adsorption of dimetridazole	adsorption capacity: 556 mg g^{-1}	74
	Al/Fe@MCC600	adsorption of non-steroidal anti-inflammatory drugs	removal rate of ibuprofen, diclofenac, naproxen, and ketoprofen: 96%, 67%, 88%, 90%, respectively	22
	α-Fe/Fe_3C	adsorption of tetracycline hydrochloride	adsorption capacity： 652 mg g^{-1}	71
	Zr-MOF	adsorption of arsenate	adsorption capacity: 86 mg g^{-1}	27
	Fe-MOF	adsorption of arsenate	adsorption capacity: 70 mg g^{-1}	27
	La-MOF	adsorption of arsenate	adsorption capacity: 114 mg g^{-1}	27
	La-MOF	adsorption of perfluorooctanoic acid	adsorption capacity: 310 mg g^{-1}	35
	Zr-MOF	adsorption of perfluorooctanoic acid	adsorption capacity: 290 mg g^{-1}	35
	UiO-66	adsorption of benzene and cyclohexane	adsorption capacity of benzene and cyclohexane: 5 mmol g^{-1} and 2 mmol g^{-1}, respectively	28
	MIL-53(Al)	adsorption of PBTC	adsorption capacity: 826 mg g^{-1}	62
	Ca-MOF	adsorption of multiple metal ions	adsorption capacity: Pb^{2+}: 644 mg g^{-1}; Cd^{2+}: 391 mg g^{-1}; Cu^{2+}:261 mg g^{-1}	75
	Fe-MOF	adsorption of Cd(II) and Pb(II)	adsorption capacity of Cd(II) and Pb(II): 143 mg g^{-1} and 259 mg g^{-1}	31
	MOF-5	adsorption of PVC and PMMA NPs	adsorption capacity of PVC and PMMA NPs: 57 mg g^{-1} and 33 mg g^{-1}, respectively	45
	UiO-66(Zr)	adsorption of water	adsorption capacity: 1.12 g_{H2O} g^{-1}	50
	MIL-101(Cr)	adsorption of water	adsorption capacity: 1.49 g_{H2O} g^{-1}	50
	MIL-101(Fe)	adsorption of water	adsorption capacity: 0.75 g_{H2O} g^{-1}	50
	MIL-88B(Fe)	adsorption of water	adsorption capacity: 0.73 g_{H2O} g^{-1}	50
	Cr-MOF	adsorption of hydrogen	H_2 uptake: 2.1 wt.%	23
	UiO-66（Zr）	adsorption of CO_2	adsorption capacity: 2.1 mmol g^{-1}	36
	MOF-5	adsorption of CO_2	adsorption capacity: 7.8 mmol g^{-1}	60
Catalysis	Ni-MOF	photodegradation of CO_2	photoreduction of CO_2, giving 9.68 × 10^3 μmol h^{-1} g^{-1} of CO with 96.7% selectivity	49
	Cu-MOF	photodegradation of acetone	93% acetone was photodegraded after 45 min	51
	MIL-53(Al,Fe)	photodegradation of tetracycline	Over 90% of tetracycline can be respectively removed within 1 h	26
	Ni/Cu-MOF@BiOI	photodegradation of MB	98% photocatalytic degradation reached within 4 h of light irradiation	55

	GO-W-MOF	photodegradation of CPF and PFF	almost complete disintegration of CPF and PFF within 60 min	56
	AIS@MIL-101(Cr)	photodegradation of tetracycline	99.98% photocatalytic degradation reached within 4 h of light irradiation	47
	Fe_3O_4@C	electro-Fenton degradation of salicylic acid	92% degradation of 50 mg L^{-1} of salicylic acid	76
	Al_2O_3/Fe_3O_4	catalytic degradation of ethylene glycol by ozone	97% EG degradation was obtained	77
	$Ru_xMn_{1.2}Co_{0.8}O_y$	oxygen evolution reaction	an overpotential of 214 mV at 10 mA cm^{-2}	32
	Cu/Zn-MOF	catalytic degradation of OPDs by $NaBH_4$	reduction reaction of OPDs by more than 95% within 12 min	58
	Cu-MOF	catalytic reduction of 4-nitrophenol by $NaBH_4$	catalytic normalized kinetic rate: 2 mol min^{-1} mg^{-1}	69
	$Co@Cr(OH)_3/ZrO_2$	hydrogen production via formic acid decomposition	TOF value of 7685 h^{-1} at 298 K	59
Energy storage	Cu-MOF	supercapacitor	capacitance: 105 F g^{-1} at 0.5 A g^{-1}	43
	Zr-MOF	supercapacitor	capacitance: 71 F g^{-1} at 0.5 A g^{-1}	43
	Ti-MOF	supercapacitor	capacitance: 56 F g^{-1} at 0.5 A g^{-1}	43
	MOF-5	supercapacitor	capacitance: 353 F g^{-1} at 0.5 A g^{-1}	61
	Zr-MOF	supercapacitor	capacitance: 890 F g^{-1} at 0.5 A g^{-1}	65
	$NiCo_2O_4$@NC	supercapacitor	capacitance: 913 F g^{-1} at1 A g^{-1}	45
	NiO_x@NPC	supercapacitor	capacitance: 581 F g^{-1} at 5 mV s^{-1}	61
	N-PC	supercapacitor	capacitance: 224 F g^{-1}	30
	$Co_{0.8}$Ni-MOF	lithium-ion battery	capacity: 1729 mAh g^{-1} at 0.5 A g^{-1}	67
	CoZn-MOF	lithium-ion battery	capacity: 1486 mAh g^{-1} at 0.5 A g^{-1}	52
	CPMD	Zn-ion capacitor	capacitance: 391 F g^{-1} at 0.5 A g^{-1}	29
Others	La-MOF	Fe^{3+} detection	limit detection: 0.147 μmol L^{-1}	33
	Tb-BDC	picric acid detection	limit detection: 1 × 10^{-5} M	66
	MIL-88B-Fe	flame retardant	MIL-88B-Fe showed synergistic flame retardancy with ADP	78

unique structural features[49]. The exceptionally high specific surface area of MOFs provides lots of active sites crucial for catalysis. Additionally, the hierarchical pore structures and substantial pore volumes facilitate the diffusion of reactants, significantly improving mass transfer efficiency. MOFs prepared from PET waste can be used as catalysts alone, with metal clusters or single--atom sites within the framework acting as densely packed, evenly distributed catalytic centers. The frameworks are capable of anchoring metal atoms, preventing metal atoms from aggregating during reactions, thus enhancing the stability of single-atom catalytic centers in MOFs. Consequently, when used alone, MOFs can deliver outstanding catalytic performance in various reactions. Furthermore, MOFs can be integrated with other materials, such as semiconductors and metal oxides, to form composite catalysts. By combining the advantages of the composed materials, the composite catalysts retain the high adsorption capabilities of MOFs while incorporating the catalytic ability of other materials, resulting in the highly effective composite catalytic systems and the high performance in the field of catalysis. Photocatalysis is a technology that utilizes light energy to drive chemical reactions. Photocatalytic reactions typically occur at room temperature and pressure, eliminating the need for high temperatures, high pressures, or strong corrosive reagents, which avoids the high energy consumption and secondary pollution issues associated with traditional thermal catalysis. MOFs prepared from PET waste, such as Ni-MOF, Cu-MOF, and MIL-53(Al, Fe), have shown promising catalytic performance in the photocatalytic degradation of CO_2, acetone, and tetracycline, respectively[26, 49, 51]. To boost the catalytic performance of MOFs, one effective strategy is to prepare composite catalysts by integrating MOFs with other materials. By combining bismuth oxyiodide (BiOI) with Ni/Cu-MOF prepared from PET waste, a composite catalyst Ni/Cu-MOF@BiOI can be prepared. Ni/Cu-MOF@BiOI (6 ppm) demonstrates excellent photocatalytic efficiency, achieving 99% degradation of MB (10 ppm) within 4 h

under sunlight exposure[55]. The integration of graphene oxide (GO) with W-MOF derived from PET waste results in a novel composite photocatalyst known as GO-W-MOF. GO-W-MOF exhibits superior photocatalytic capabilities, particularly in the degradation of organophosphorus pesticides such as chlorpyrifos (CPF) and profenofos (PFF). Under the optimized conditions of a catalyst dosage of 0.6 g L^{-1}, a pH value of 5, and initial CPF and PFF concentrations of 1 mg L^{-1}, CPF and PFF are effectively degraded within just 60 min[56]. By evenly attaching $AgInS_2$ nanoparticles onto MIL--101(Cr), a composite catalyst $AgInS_2$@MIL-101(Cr) can be created. When the loading of $AgInS_2$ reaches 40%, the composite catalyst demonstrates exceptional photocatalytic performance, achieving nearly 99% degradation of tetracycline in solution after just 4 h of light exposure[47]. By subjecting MOFs synthesized from PET waste to thermal decomposition, it is possible to produce oxide or carbon-oxide materials that serve effectively as catalysts, which have shown good catalytic performance in various reactions such as electro-Fenton degradation of salicylic acid, ozone degradation of ethylene glycol, and the oxygen evolution reaction (OER)[32, 76, 77]. Moreover, MOFs prepared from PET waste have demonstrated excellent catalytic performance in several reactions, including the catalytic degradation of organic pollutant dyes (OPDs) and 4-nitrophenol using sodium borohydride,as well as hydrogen production through formic acid decomposition[58, 59, 69].

The outstanding physicochemical properties of MOFs prepared from PET waste make them highly promising for energy storage applications[43]. The high specific surface area of MOFs can provide numerous active sites for energy storage devices, which helps enhance energy density and storage efficiency. The unique pore structures not only facilitate ion transport but also effectively accommodate more charge carriers, thereby enhancing overall energy storage performance. By designing novel MOF-derived structures, further optimization of the physicochemical properties of the MOFs prepared from PET waste can be achieved. For example, adjusting synthesis conditions allows for the tuning of pore size, morphology, and surface characteristics to meet the demands of specific energy storage applications. Modulating the types of metals within MOFs prepared from PET waste can significantly improve surface properties, porosity, and electrical conductivity. Different metal centers may offer varied electronic environments, impacting the electrochemical performance. Moreover, the carbonization of MOFs prepared from PET waste enhances their electrical conductivity, a crucial factor for energy storage applications, especially in scenarios requiring rapid electron transfer such as supercapacitors and batteries. Therefore, MOFs prepared from PET waste are suitable as electrode materials for supercapacitors, offering high capacity and fast charge/discharge capabilities[79, 80]. Additionally, these MOFs can be applied in lithium-ion batteries or other battery types, serving as electrode materials or separator coatings to improve overall battery performance. MOFs prepared from PET waste can be directly used as active electrode materials for supercapacitors. Cu-MOF, MOF-5, and Zr-MOF exhibit specific capacitances exceeding 100 F g^{-1} at a current density of 0.5 A g^{-1}[43, 64, 65]. By carbonizing the synthesized MOFs, high-performance electrode active materials can also be produced[30, 61]. For example, after preparing bimetallic MOFs (Ni/Co-MOF) from PET waste, followed by carbonization under nitrogen protection at 450 °C and oxidation in air at 230 °C, $NiCo_2O_4$@NC nanocomposites can be successfully fabricated. When $NiCo_2O_4$@NC is used as the active material for supercapacitors, the assembled supercapacitor achieves a specific capacitance of 913 F g^{-1} at 1 A g^{-1}[45]. MOFs synthesized from PET waste have shown potential for direct use as active electrode materials in lithium-ion batteries[67, 81]. By mixing $Co(NO_3)_2 \cdot 6H_2O$ and $Zn(NO_3)_2 \cdot 6H_2O$ with TPA derived from PET waste, and using a solvent mixture of DMF/H_2O in a 4:1 volume ratio, CoZn-MOF can be synthesized. When CoZn-MOF is utilized as the electrode material for lithium-ion batteries, it exhibits a discharge-specific capacity of 1485.5 mAh g^{-1} after 100 cycles at 0.5 A g^{-1}[52]. Zinc-ion capacitors are energy storage devices that combine the features of batteries and supercapacitors, which are gaining attention for potential use in portable electronics and electric vehicles[82–84]. Using MIL-53(Al) prepared from PET waste as a precursor, a carbon material called CPMD can be synthesized through carbonization and acid washing. CPMD is an excellent electrode material for zinc-ion capacitors. When used as the electrode material in a zinc-ion capacitor, the device achieves a specific capacitance of 391 F g^{-1} at a current density of 0.5 A g^{-1}[29].

The exploration of applications for MOFs synthesized from PET waste is continuously expanding their potential uses. One particularly promising area leverages the ability of certain metal-organic frameworks to produce significant fluorescence signals and exhibit distinct emission colors. These properties enable the development of MOF-based materials for the detection of various ions and small molecules[66]. For example, through the ball milling method, $La(NO_3)_3 \cdot 6H_2O$ can be combined with TPA obtained from PET waste to synthesize Ln-MOF, which shows remarkable sensitivity, achieving a detection limit for iron ions (Fe^{3+}) as low as 0.147 μmol L^{-1}[33]. The combination of MIL-88B-Fe prepared from PET waste and aluminum diethylphosphinate (ADP) demonstrates a synergistic flame retardancy in epoxy resin (EP). When a mixture containing 8% of MIL-88B-Fe and ADP is added to EP, the resulting flame-retardant EP achieves a V0 rating in the UL-94 test[78].

Therefore, through the above applications, MOFs derived from PET waste demonstrate significant potential in addressing environmental challenges while improving industrial processes.

CONCLUSIONS AND FUTURE PERSPECTIVES

The preparation methods and applications of MOFs prepared from PET waste indicate that research in this area remains in a phase of rapid development, with significant potential for sustainable development and environmental protection. However, several challenges persist:

Purity and stability issues: The complexity of PET waste, including additives such as plasticizers, can interfere with MOFs synthesis, resulting in low crystallinity

and unstable porosity. Impurities such as metals, paper-based labels, and adhesives in recycled PET also affect the structure and performance of MOFs.

High synthesis costs: High-purity metal salts and organic ligands are required for the synthesis of high-performance MOFs. The conversion process of PET waste involves complex modification steps (e.g., acid hydrolysis), leading to higher energy consumption and reagent use compared to traditional raw materials. Additionally, solvent recovery further increases production costs.

Limited application scenarios: Since the organic ligand of PET-based MOFs is limited to TPA, gaps exist in structural regulation, pore size distribution, and thermal stability when compared to MOFs produced by traditional methods. These limitations restrict their application in areas such as gas adsorption and catalysis.

To address these challenges and promote the large-scale application of technologies that convert PET waste into MOFs, the following pathways can be pursued.

First, establishing a recycling system for PET waste to produce MOFs. Standards for the recycling of PET waste can be established and promoted to ensure that the collected PET waste meets the requirements for the preparation of MOFs. The purity of PET waste can be guaranteed through measures such as the encouragement of using water-washable labels. Additionally, mechanical recycling and chemical recycling technologies can be integrated to form a combined "sorting-depolymerization" production line for PET waste, through which PET materials with different levels of purity and quality can be scientifically and efficiently recovered and utilized.

Second, promoting innovation in green synthesis technologies. The development of low-energy PET depolymerization technologies such as enzymatic degradation can be pursued to enhance the purity of monomer recovery while reducing energy consumption. Industrial-scale alternative raw materials can be implemented by directly utilizing metal waste as the metal source for MOFs, through which the overall production cost can be effectively lowered. In addition, membrane separation technology can be integrated to optimize solvent recovery systems, enabling efficient collection and reuse of solvents employed during the preparation process of MOFs.

Finally, optimizing the structure of MOFs prepared from PET waste and expanding application scenarios. High-performance composite MOFs can be developed through the incorporation of materials such as graphene and biochar. Post-synthetic modification techniques such as amine functionalization can be applied to produce PET-derived MOFs with targeted functionalities. Furthermore, the application of PET-based MOFs in environmental remediation can be explored, including the use of high-performance PET-derived MOFs for capturing microplastic particles in water and for photocatalytic degradation of organic pollutants.

The conversion of non-degradable PET waste into MOFs not only addresses environmental pollution caused by PET waste but also achieves comprehensive resource utilization, aligning with the principles of green chemistry. Therefore, upcycling PET waste into MOFs represents an innovative strategy that supports environmental protection efforts while simultaneously creating opportunities for utilizing waste as a resource, thereby contributing positively to both economic and ecological sustainability.

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