



Sustainable MOFs from waste PET: bridging polymer recycling with advanced material applications

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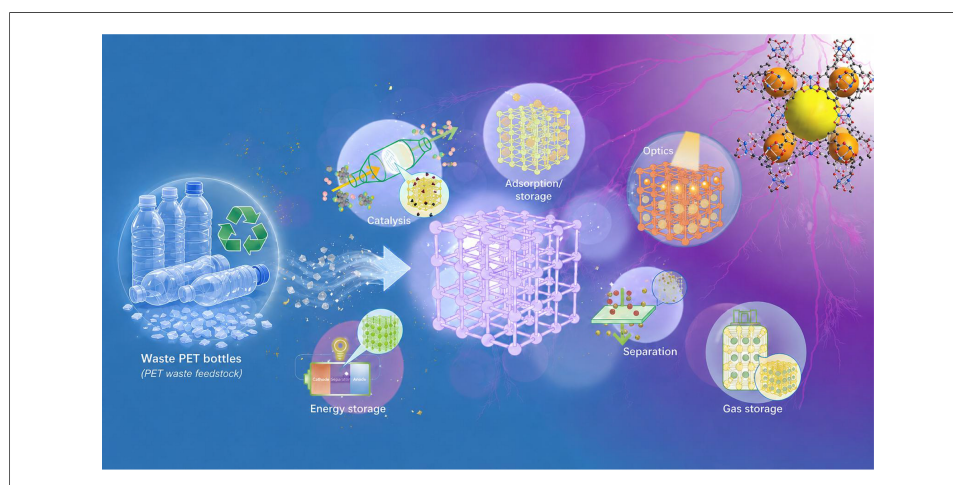
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Abstract

The increasing accumulation of polyethylene terephthalate (PET) waste poses significant environmental challenges due to its complex composition and difficulty in recycling. Metal-organic frameworks (MOFs) derived from PET have emerged as a promising solution, offering high porosity, tunable chemistry, and versatile functionality for various applications. This review comprehensively summarizes recent progress in the synthesis of PET-derived MOFs, including two-step, one-pot, mechanochemical, microwave-assisted, and *in situ* growth strategies, with particular attention to the conversion of complex waste PET feedstocks. The applications of PET-derived MOFs are then reorganized into adsorption and separation, catalysis, energy storage and conversion, sensing and detection, and emerging functional applications. Particular emphasis is placed on CO₂ capture and gas separation, wastewater purification, pollutant degradation, electrochemical energy storage, molecular sensing, flame protection, passive thermal management, and functional composite materials. By integrating insights into synthesis, structure-property relationships, and functional applications, this review also highlights the potential of PET-derived MOFs as sustainable materials for next-generation energy and environmental technologies, bridging the gap between polymer waste recycling and advanced material design.

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INTRODUCTION

Polyethylene terephthalate (PET) is a crucial polymer in global packaging and industrial sectors^[1-3]. Its lightweight, durable, and thermally stable properties make it ideal for manufacturing bottles and films^[4-6]. The rising demand for sustainable packaging, together with the continued growth of the beverage, food, automotive, and electronics industries, has markedly expanded the PET market. Meanwhile, advances in PET recycling technologies have further increased interest in its circular utilization and high-value conversion. However, the PET industry faces significant challenges, notably in environmental sustainability. Plastic pollution and volatile raw material prices are major hurdles to further growth. Global PET production exceeds tens of millions of tons annually, with 2023 seeing production of PET bottle flakes at about 39.39 million tons and global polyester-based PET material output around 71 million tons. Polyester-based PET materials lead this market, comprising about 57% of global consumption [Figure 1]^[7,8]. Nevertheless, effectively managing this PET waste remains a significant challenge. By 2023, the global plastic waste recycling rate was merely 9%, and PET recycling rates were similarly low. Although the European Union and China boast PET recycling rates above 50%, a significant amount of PET waste is still landfilled or incinerated, leading to severe environmental impacts^[9]. Complex PET-rich waste recycling is particularly challenging because dyes, auxiliary chemicals, and blended materials obstruct efficient recovery and reuse^[10-13]. Overcoming these recycling barriers is essential for reducing PET-related environmental harm and advancing a circular economy.

PET is categorized into film-grade and bottle-grade polyester based on its applications. Polyester bottle flakes, representing roughly 20%, are chiefly used in food and beverage packaging. Polyester film, accounting for about 5%, is mainly employed in outer-layer materials due to its superior printability^[14-16]. A large share of this PET waste is exported to developing countries, where approximately 40% eventually ends up in landfills or oceans, worsening microplastic pollution^[17]. The pervasive use of PET

links it directly to the fossil fuel sector, significantly contributing to carbon emissions. Conversely, PET, predominantly used in bottles and films, is extensively utilized in food, beverage, and other packaging applications. Despite the high recyclability of PET bottles, the global recycling rate lingers below 50%, with significant quantities of PET plastic still entering the ocean annually, inflicting severe environmental harm. Improving recycling infrastructure and advancing innovative recycling techniques are crucial to mitigating its ecological impact and fostering sustainability in the polymer industry.

On the other hand, metal-organic frameworks (MOFs) have emerged as a versatile class of porous materials with immense potential across a range of applications. Their high porosity, structural tunability, and diverse functionality have enabled their use in catalysis^[18-20], controlled drug delivery^[21], gas adsorption and separation^[22,23], pollutant remediation^[24-26], and energy storage^[27,28]. The utilization of waste-derived precursors in MOF synthesis has emerged as a promising strategy to address the limitations associated with conventional MOF fabrication methods. Conventional MOF synthesis often relies on costly organic ligands and stringent reaction conditions, which impede large-scale industrial deployment^[29-31]. Researchers have increasingly explored the incorporation of waste-derived raw materials, such as PET containing terephthalic acid (TPA) structural units, into MOF synthesis. This approach aims to reduce costs and enhance environmental sustainability^[32-34]. PET has emerged as a promising source of organic ligands for MOF production. The chemical depolymerization of post-consumer PET waste into its constituent TPA presents a viable strategy to enhance the value-added utilization of this ubiquitous polymer. This approach not only increases the economic viability of PET recycling but also offers a cost-effective pathway for the production of MOFs, thereby promoting sustainable material lifecycles and resource conservation. Recent advancements in MOF synthesis from waste PET have notably improved the recycling and valorization of bottle-grade PET. Nonetheless, PET recycling remains challenging due to its complex composition, high processing costs, and the lack of

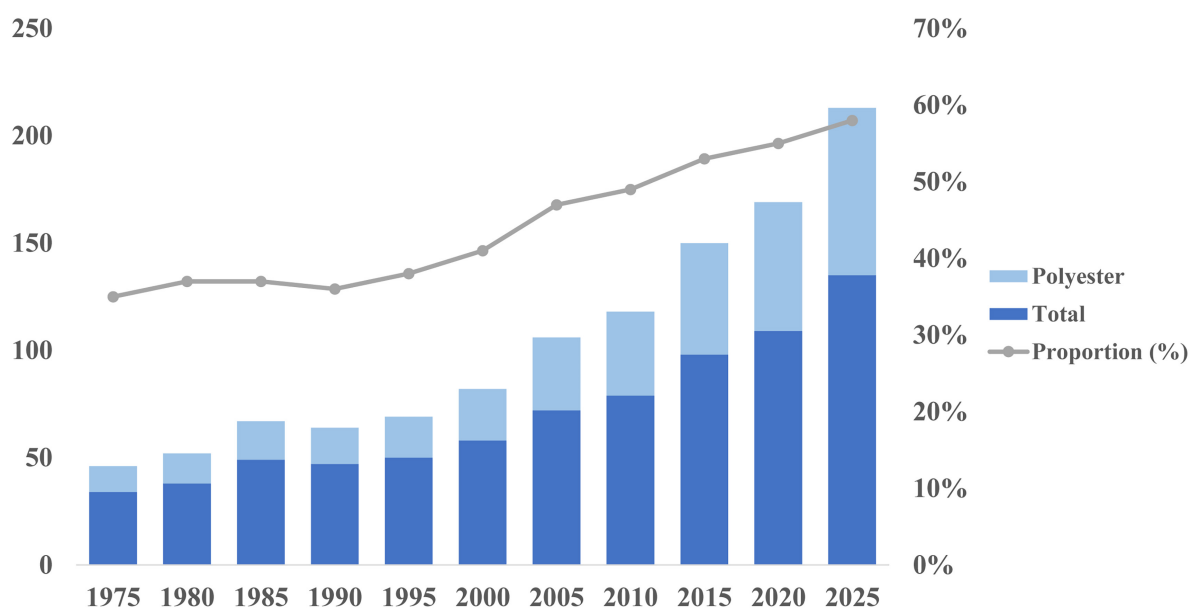


Figure 1. Global polyester-based PET material production (million tonnes). This original data visualization was plotted using data from references^[7,8]. PET: Polyethylene terephthalate.

mature technological solutions. This review systematically explores recent advancements in synthesizing MOFs from recycled PET (rPET), emphasizing strategies for effectively utilizing PET waste in MOF production. It also analyzes the limitations of current technologies and suggests future research directions to enhance sustainable PET resource utilization.

Literature search strategy and selection criteria

This review used a transparent narrative-search approach to identify literature on the conversion of waste PET into MOFs, associated PET-depolymerization routes, and applications of PET-derived MOFs. Searches were organized around combinations of terms describing PET waste, TPA or terephthalate recovery, MOF synthesis, hydrolysis, glycolysis, mechanochemistry, microwave processing, one-pot conversion, *in situ* growth, adsorption, separation, catalysis, energy storage, sensing, scale-up, techno-economic feasibility, and life-cycle or environmental assessment.

Peer-reviewed research articles and reviews directly relevant to PET-to-MOF conversion or to the interpretation of industrial, economic, and environmental constraints were prioritized. Studies were retained when they reported a clearly identifiable synthesis route, PET-derived feedstock or compara-

tor material, characterization or application data, or evidence relevant to scale-up and sustainability. Publications lacking sufficient methodological detail, items unrelated to PET-derived terephthalate chemistry, and duplicate reports of the same work were not used as primary evidence. Reference lists of relevant papers were also examined to identify additional studies.

Because complete contemporaneous records of the original searches, exact search dates, database-specific strings, and screening counts were not available, this review is not presented as a systematic review, and no Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-style selection counts are claimed. The resulting evidence base should therefore be interpreted as a structured narrative review rather than an exhaustive bibliometric census.

METHODS FOR RECYCLING WASTE PET

The production, use, and recycling of PET expose the material to environmental stressors, including light, heat, oxidation, and biological activity, which induce molecular degradation. This degradation process manifests as a reduction in molecular weight and mechanical properties, thereby constraining the direct reuse of PET waste. To address these challenges, a range of PET recycling methods have been

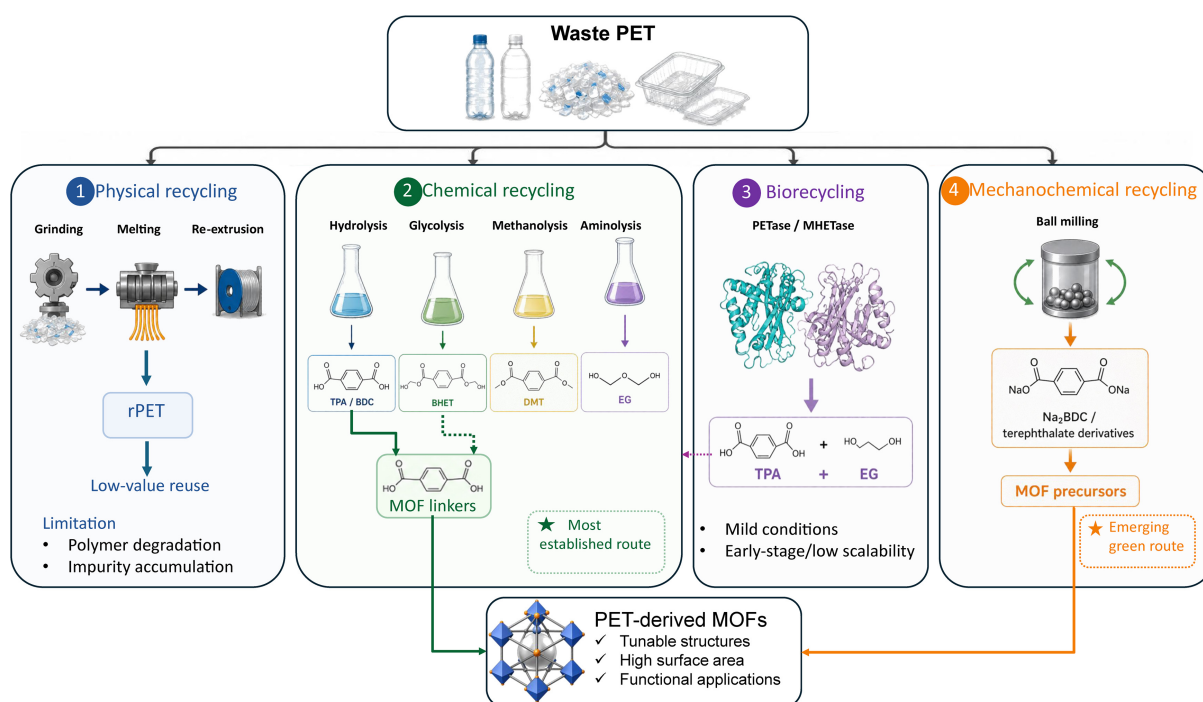


Figure 2. Waste PET feedstock complexity and representative upcycling routes toward PET-derived MOFs. PET: Polyethylene terephthalate; MOFs: metal-organic frameworks.

developed, including physical, chemical, biological, and mechanochemical approaches [Figure 2]. Physical recycling utilizes mechanical processing techniques, such as grinding, melting, and re-extrusion, to produce rPET. However, this approach is limited by material degradation and impurity accumulation. Depolymerization of PET through chemical recycling techniques, such as hydrolysis, glycolysis, methanolysis, or aminolysis, can yield high-purity monomers or oligomers for reuse. Biological recycling, which employs enzymatic pathways, offers a milder approach to PET degradation, though its industrial application remains in the early stages. Mechanochemical recycling, particularly ball milling, provides a solvent-free route to PET depolymerization and has garnered attention as a potential method for the preparation of MOF precursors. Chemical and mechanochemical recycling are the most pertinent approaches for converting PET into MOF materials, as they enable the selective recovery of TPA or its derivatives. The subsequent sections will offer a comprehensive examination of each method, emphasizing its applicability, advantages, and limitations in the context of PET-to-MOF conversion.

Physical recycling

Physical recycling of waste PET involves mechanical processing through cutting, crushing, heating, and remelting to produce rPET. This approach is economically viable and environmentally sustainable and requires minimal technical intervention. However, the resulting rPET exhibits inferior mechanical properties compared to virgin PET due to contamination and polymer degradation, restricting its use to lower-value applications. Moreover, repeated recycling progressively deteriorates material performance, limiting its suitability for high-quality applications, such as food-grade packaging^[35–38].

Chemical recycling

Chemical recycling breaks down PET waste into low-molecular-weight intermediates or monomers under controlled conditions. Various degradation pathways produce different products. Glycolysis, a well-established method, utilizes ethylene glycol (EG) to decompose PET into bis(2-hydroxyethyl) terephthalate (BHET), which can be further transformed into TPA^[39–42]. While BHET can be used as a precursor for MOF synthesis, benzene-1,4-dicarboxylic acid (BDC) is favored for its superior processability^[43]. Nonetheless, glycolysis is economically challenged, as its products do not pro-

vide a cost advantage over virgin petrochemical feedstocks^[44]. Methanolysis breaks down PET into dimethyl terephthalate (DMT) and EG under liquid-phase, steam-phase, or supercritical conditions, with product yield heavily influenced by reaction conditions and subsequent purification^[45–47]. Hydrolysis under alkaline, acidic, or neutral conditions typically yields BDC in high yields (~100%), and enables monomer recovery under relatively mild conditions^[48–55]. Accumulating evidence suggests that particle size and surface area are often more influential on depolymerization efficiency than reaction temperature^[56–61]. Catalyst selection is a critical factor in reaction kinetics and efficiency, with a range of options including alkaline and acidic catalysts^[62], quaternary ammonium salts^[63], ionic liquids^[64–66], and metal salts^[67]. However, chemical recycling frequently necessitates intricate separation procedures and produces waste, presenting challenges for large-scale sustainable implementation^[68,69].

Biorecycling

Biorecycling employs enzymes to degrade PET, presenting an eco-friendly method with minimal waste production^[70–72]. The bacterium *Ideonella sakaiensis* can break down PET at moderate temperatures (30–37 °C) through the combined action of PETase and MHETase, which cleave ester bonds to produce TPA^[73–78]. Despite its promise, enzymatic PET degradation remains nascent, facing challenges in efficiency, scalability, and industrial application that necessitate further refinement^[79].

Mechanochemical recycling

Mechanochemical recycling via ball milling allows PET depolymerization under mechanical stress without extreme conditions or harsh solvents^[80,81]. The high-energy impacts during milling facilitate bond cleavage, breaking PET into monomers like disodium terephthalate (Na₂BDC) and EG^[82]. Inadequate milling may leave residual unreacted polymer and impurities, complicating subsequent separation and purification^[83].

While biorecycling and mechanochemical recycling offer environmental sustainability and cost-effectiveness, they remain in nascent stages and need further refinement for large-scale application. In contrast, chemical recycling is the most widely used method, owing to its efficiency and established processes. The sustainability and cost-effectiveness of PET recycling

have motivated ongoing research to refine existing methods. In the context of PET-derived MOF synthesis, chemical recycling remains the predominant strategy, while mechanochemical approaches are garnering increasing interest due to their solvent-free and energy-efficient attributes.

STRATEGIES FOR CONVERTING PET WASTE INTO MOFS

PET, a widely used polymer composed of TPA and EG monomers, serves as a valuable precursor for MOF synthesis due to its high TPA content (over 80 wt%). Several strategies have been devised to convert waste PET into MOFs, including two-step, one-pot, *in situ* growth, and ball milling techniques, with some studies employing microwave-assisted methods to boost reaction efficiency. These approaches enable the transformation of PET into various MOF materials, such as UiO-66, MIL-53, MIL-101, and ZIF-8.

Two-step method

The two-step approach enables independent optimization of PET degradation and MOF synthesis. Initially, PET undergoes chemical depolymerization into monomers or oligomers, such as TPA or its esters^[84]. These degradation products are then purified and employed as linkers in MOF synthesis. As a polyester containing ester bonds, PET can be chemically depolymerized into valuable intermediates via hydrolysis^[32,85–89], alcoholysis^[90–94], or aminolysis, as depicted in Figure 3.

Hydrolysis method of waste PET

Acidic hydrolysis

Acidic hydrolysis uses concentrated sulfuric, nitric, or phosphoric acid as catalysts to swiftly convert PET into high-purity TPA and EG. For instance, Dermanaki Farahani *et al.* attained over 99% TPA purity by degrading PET at room temperature with concentrated sulfuric acid, followed by two pH adjustments^[85]. While efficient, this approach produces substantial inorganic salt waste and presents equipment corrosion issues. Efforts to recycle acid catalysts address environmental concerns but typically necessitate prolonged reaction times and high temperatures, restricting large-scale application^[95].

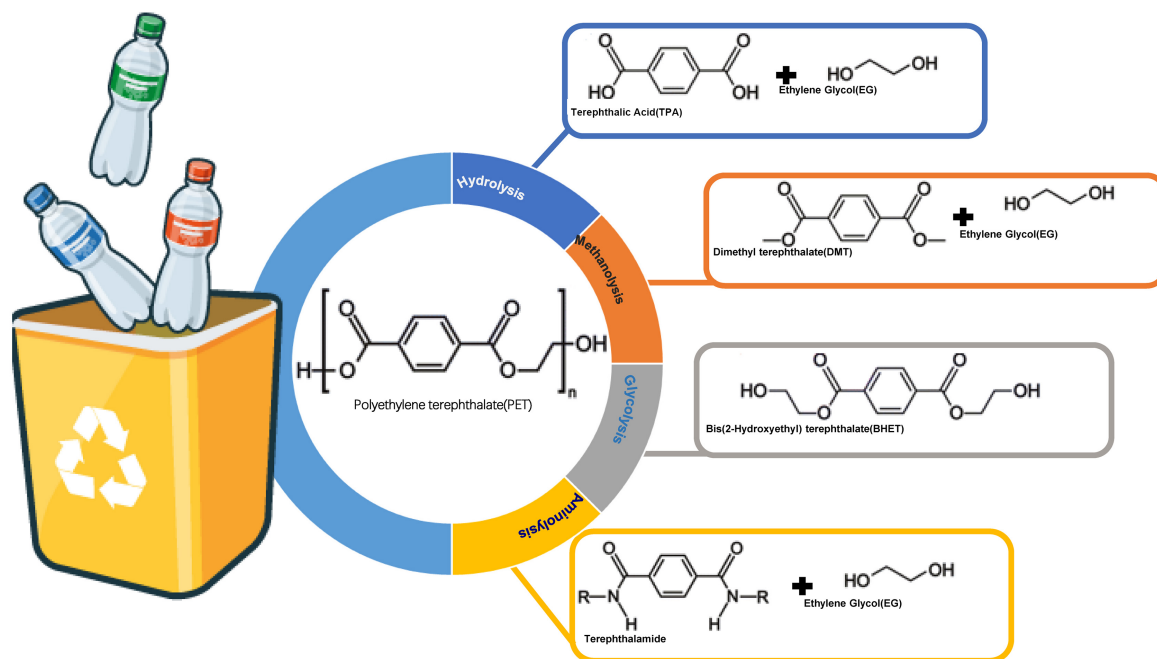


Figure 3. Various chemical methods for depolymerizing PET and their corresponding products. PET: Polyethylene terephthalate; TPA: terephthalic acid; EG: ethylene glycol; DMT: dimethyl terephthalate; BHET: bis(2-hydroxyethyl) terephthalate.

Alkaline hydrolysis

Alkaline hydrolysis in 4%-20% sodium hydroxide (NaOH) or potassium hydroxide (KOH) solutions effectively recovers high-purity TPA from PET. Complete degradation into terephthalate salts (Na_2TPA or K_2TPA) typically requires high temperature and pressure. However, direct use of these salts in MOF synthesis can lead to undesired hydroxide incorporation, reducing the specific surface area of the final material^[96]. Therefore, a post-treatment step involving acidification (e.g., H_2SO_4 or HCl) and recrystallization is commonly employed to obtain high-purity BDC suitable for MOF synthesis^[97,98].

Recent advancements have markedly enhanced the efficiency and sustainability of alkaline hydrolysis. Rotary autoclave-assisted hydrolysis improves TPA recovery, while techniques like microwave, plasma, and ultrasound accelerate degradation kinetics^[99]. Allaf *et al.* reduced hydrolysis time from 3 h to 5 min using microwave irradiation, with gamma rays and ultraviolet (UV) pre-irradiation further increasing yield^[100]. Jung *et al.* achieved nearly complete PET conversion (> 99.9%) through ultrasound-assisted hydrolysis^[87]. Štrukil *et al.* developed an integrated approach combining ball milling and

alkaline hydrolysis, which enabled near-quantitative TPA yields under mild conditions while minimizing alkali consumption, thereby reducing the environmental impact^[101]. Building upon this work, Wang *et al.* further optimized the process by introducing an alcohol or ether co-solvent system, facilitating highly efficient PET degradation (TPA purity: 99.73%) under mild conditions (80 °C, 60 min)^[102]. These innovations address the limitations of traditional high-temperature, long-duration hydrolysis methods and enhance the overall sustainability of PET conversion.

Alcoholysis

Alcoholysis, generally conducted in EG with a catalyst, primarily produces DMT or BHET, with oligomer formation also common. Traditional methods necessitate 210 °C for 8 h^[93,103], though optimization can mitigate these harsh conditions^[104,105]. Despite these advancements, industrial application faces hurdles, notably low TPA yields (~55%) and complicated purification processes. Researchers have investigated deep eutectic solvents (DESSs) as catalysts to overcome existing limitations, offering a unique reaction environment that boosts BHET yield and significantly shortens glycolysis time^[106]. A solvent-free “grind-bake” method has also been devel-

oped for converting PET-derived BHET into MOFs. This approach facilitates the efficient mechanochemical synthesis of UiO-66(Zr) and alkaline-earth-metal BDC-based MOFs (e.g., Ca-BDC, Ba-BDC)^[107]. By eliminating the need for organic solvents, this method simplifies reaction steps, adheres to green chemistry principles, and expands the potential use of alcoholysis-derived PET intermediates in MOF synthesis.

Hydrolysis of colored PET waste

Using colored PET in MOF synthesis presents additional complexities compared to clear PET. The presence of dyes and additives can interfere with the crystallization and porosity of the resulting MOFs. For instance, Dyosiba *et al.* reported that alcoholysis-derived BDC from colored PET produced MOFs with reduced specific surface areas ($933\text{--}1,085\text{ m}^2\cdot\text{g}^{-1}$) compared to those derived from commercial BDC ($1,368\text{ m}^2\cdot\text{g}^{-1}$)^[34]. Similarly, Andini *et al.* observed reduced yields of BHET from dye-containing PET waste compared to undyed counterparts^[10].

To address these limitations, researchers have devised dye-removal strategies. Chang *et al.* effectively hydrolyzed colored PET waste using HNO_3 , employing acid-mediated dye degradation to obtain high-purity TPA, which facilitated the synthesis of catalytically active UiO-66^[108]. Another method uses EG vapor-assisted decolorization, where dye molecules are selectively dissolved and removed before alcoholysis, achieving decolorization rates over 90.2%^[109]. These advancements improve the feasibility of upcycling colored PET for MOF synthesis and create new opportunities for sustainable PET recycling.

Second step: MOF synthesis

In this phase, degradation products from the initial step, such as TPA or its salts, react with metal salts and organic ligands to synthesize MOF materials [Figure 4]. For instance, TPA from the alkaline hydrolysis of waste PET bottles can react with $\text{Cu}(\text{NO}_3)_2\cdot 3\text{H}_2\text{O}$ to form Cu-based MOFs with high porosity^[86]. As MOF varieties and synthesis techniques rapidly expand, common methods include hydrothermal/solvothermal synthesis, assisted synthesis methods, and mechanical ball milling. Hydrothermal/solvothermal synthesis remains the most established, while ball milling is gaining atten-

tion for its eco-friendly and efficient nature.

Hydrothermal/Solvothermal method

The solvothermal synthesis method is commonly employed to produce MOFs. This approach involves placing reactants in a reactor containing water or an organic solvent, and applying autogenous pressure at elevated temperatures to facilitate the slow nucleation and growth of MOF crystals. This technique has been successfully utilized to synthesize a range of well-established MOFs, including MOF-5(Zn)^[98,115–117], MIL-101(Cr)^[118–122], MIL-53(Al)^[123–126], and UiO-66(Zr)^[34,100,107,116,127–130]. Fe-MOFs^[87,96,100,116,131], Cu-MOFs^[32,86,95,97,132,133], and Ca-MOFs^[85,107,134,135] are commonly synthesized using this method. However, hydrothermal/solvothermal synthesis typically necessitates significant amounts of toxic solvents like *N,N*-dimethylformamide (DMF) and hydrofluoric acid (HF) and involves high-temperature and high-pressure conditions^[85,136], resulting in elevated costs and energy consumption.

To address these challenges, researchers have developed several optimization strategies. These include the use of water-soluble organic ligands^[96], the adoption of solvent-free synthesis techniques^[107,129], and the promotion of reactions through stirring instead of high-temperature treatments^[137]. Furthermore, studies have demonstrated that MIL-101(Cr) synthesized under HF-free conditions can exhibit comparable specific surface area and gas adsorption performance, thus eliminating the need for HF^[138–140]. Citric acid, dimethyl sulfoxide (DMSO), and trifluoroacetic acid (TFA) have been investigated as environmentally benign alternatives to H_2SO_4 and HNO_3 for the synthesis of MOFs^[141]. These modified approaches not only reduce the costs and energy demands of the synthesis process but also enable the scalable production of MOFs from waste-derived feedstocks. This advancement supports efforts to mitigate global plastic pollution and facilitate the commercial deployment of MOF-based technologies.

Assisted synthesis methods

Emerging auxiliary technologies, such as microwave-assisted^[142] and electrically assisted^[143] synthesis, have been explored to optimize MOF fabrication. For instance, TPA derived from PET waste can be used to synthesize MOFs via microwave-as-

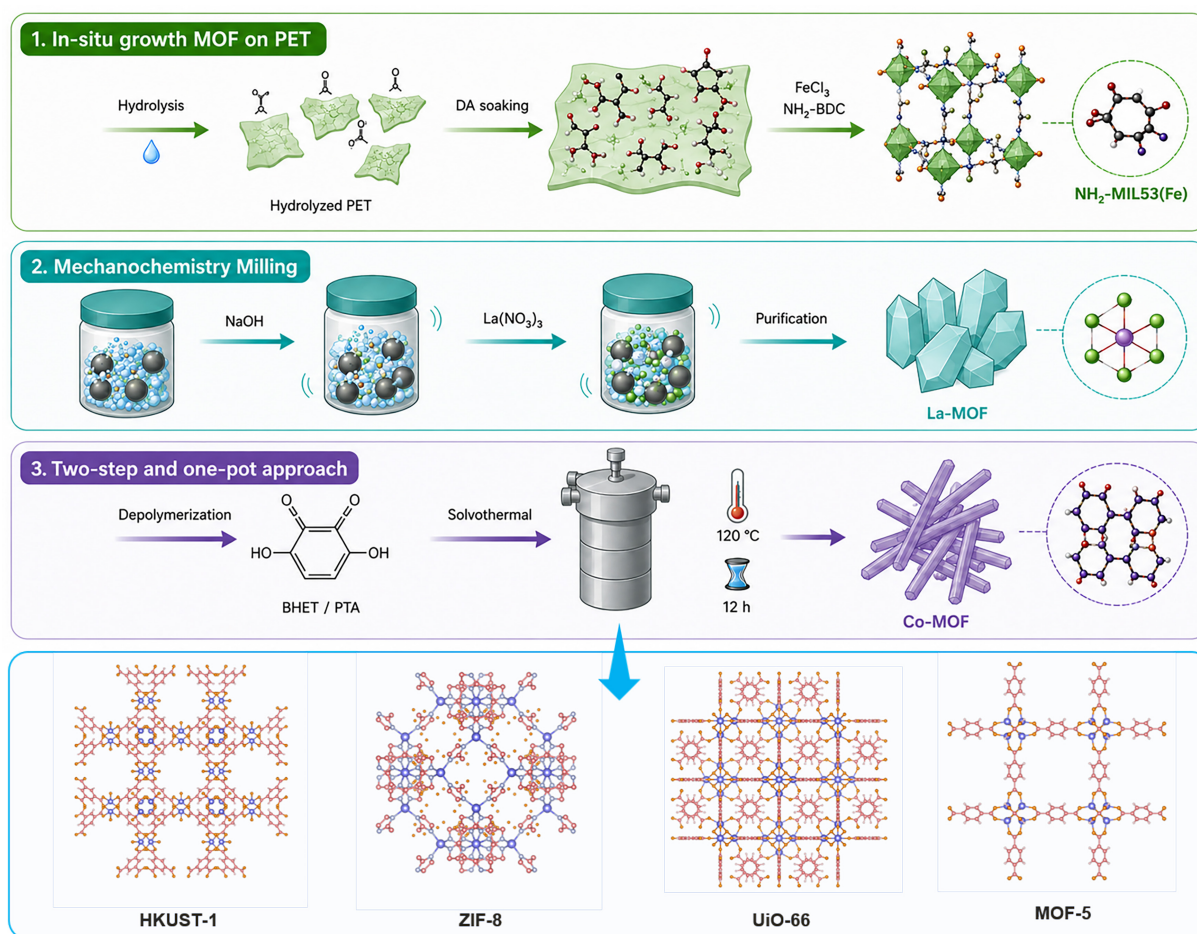


Figure 4. Various synthesis methods for PET-derived MOFs and schematic representations of selected MOF structures (HKUST-1, ZIF-8, UiO-66, and MOF-5). The crystal structures were independently rendered by the authors using VESTA based on crystallographic data reported in the corresponding original publications: HKUST-1 (CSD Refcode: FIQCEN)^[110], ZIF-8 (CSD Refcode: OFERUN)^[111], UiO-66 (CSD Refcode: RUBTAK)^[112], and MOF-5 (CSD Refcode: SAHYIK)^[113], with crystallographic data obtained from the CSD^[114]. CSD: Cambridge Structural Database; MOFs: metal-organic frameworks.

sisted methods. Compared to traditional solvothermal approaches, microwave-assisted synthesis of MOF-5 and Cu-MOF yields materials with identical crystalline structures, while significantly accelerating crystal growth, reducing reaction times to approximately five min, and improving overall yield^[32]. Moreover, microwave irradiation enables precise control over MOF morphology and particle size, enhancing material performance for targeted applications.

Mechanical ball milling

Mechanical ball milling, an eco-friendly and solvent-free synthesis method, is applicable for both alkaline hydrolysis of PET and direct MOF synthesis^[144]. During this process, PET degrades into terephthalate ions when milled with NaOH. These ions then react with metal precursors under

mechanochemical forces, forming short-range ordered structures that yield metal-based MOFs (e.g., Cu, Ca, La)^[99,145,146].

The two-step ball milling method has been further optimized, enabling direct mechanochemical synthesis of MOFs through assisted alkaline hydrolysis. This approach has facilitated the synthesis of a variety of MOFs, including those based on La, Zr, Ni, Co, Mn, and Ca, with large-scale production of Ni-MOF already demonstrated^[147]. The ongoing advancements in ball milling techniques underscore its potential as a scalable and sustainable pathway for MOF synthesis, particularly from waste-derived precursors.

One-pot method

The one-pot method enables the simultaneous

depolymerization of waste PET and crystallization of MOFs within a single reaction system, eliminating the need for intermediate separation or complex post-synthetic modifications. First reported by Ren *et al.*^[90] and Deleu *et al.*^[148] in 2016, this approach provides a green, efficient strategy for directly converting waste PET into MOF materials. By incorporating all reactants - metal salts, organic linkers, solvents, and acid/base regulators - into a unified system, researchers have successfully synthesized BDC-based MOFs from PET precursors, including MIL-47(V), MIL-53(Cr, Al, Ga), and MIL-101(Cr)^[149]. Since its development, the one-pot method has been extensively explored for synthesizing mixed-ligand MOFs, further broadening the scope of PET-derived ligands in MOF synthesis^[150].

Key considerations in the one-pot method

Complete PET degradation is crucial for successful MOF formation in a one-pot process. Elevated temperatures and extended durations are typically required to ensure full hydrolysis of PET into terephthalate ions (BDC²⁻), preventing the precipitation of unstable oxides or hydroxides due to incomplete ligand formation^[148]. Furthermore, the degree of deprotonation of BDC significantly influences the stabilization of the MOF framework^[151-153].

DMF is often employed as a solvent in the one-pot synthesis method due to its ability to both dissolve reactants and promote H₂BDC deprotonation, aiding the formation of stable MOFs like MIL-53(Al), UiO-66, and MOF-5^[154-157]. Nonetheless, concerns over DMF's toxicity and environmental impact have driven the exploration of greener alternatives. Acetone, for example, has been effectively utilized as a solvent, with formic acid serving as a crystallization regulator, to synthesize UiO-66 in one step^[158]. A promising method uses Na₂BDC, derived from PET through alkaline hydrolysis, as a precursor, streamlining reaction steps and minimizing environmental impact. The acidic conditions in the one-pot process both dissolve metal ions and subtly adjust carboxyl group deprotonation, allowing for controlled crystal growth. For instance, MOFs like MIL-53(Cr), MIL-101(Cr), and MIL-47(V) have been hydrothermally synthesized in DMF using HF as a growth modifier^[149]. However, due to rising environmental and safety concerns, HF has been largely replaced by less toxic alternatives such as hydrochlo-

ric and acetic acids, which preserve crystal quality while minimizing risks^[159-162].

Alkaline conditions, such as those provided by NaOH or KOH, facilitate the direct formation of BDC²⁻ from PET hydrolysis, bypassing the need for a deprotonation step. These conditions also prevent the formation of metal hydroxides or oxides, enhancing the purity of MOF products. To enhance metal ion stability, localized pH adjustments using weak acids like acetic acid facilitate low-temperature, rapid synthesis, exemplified by Cu-MOF production^[153]. Bai *et al.* and Fan *et al.* further streamlined the process by synthesizing Co-MOF and Mn-MOF without acids or bases, but this method necessitates high temperatures, leading to increased energy consumption and equipment demands^[163,164].

Emerging approaches for green and efficient one-pot synthesis

Amid increasing focus on sustainable chemistry, researchers are investigating innovative reaction systems like ionic liquids and microwave-assisted techniques to improve PET depolymerization and MOF synthesis^[165,166]. Functionalized ionic liquids act as acid/base catalysts, enhancing both the efficiency and selectivity of depolymerization^[167,168]. For example, Ni-MOF nanorods were synthesized using an N-methyl-2-pyrrolidone-nickel(II) chloride (NMP-NiCl₂) ionic liquid system, where NMP aided in PET dissolution and provided a biodegradable, sustainable option for one-pot MOF synthesis^[169,170].

The one-pot method offers a compelling approach for large-scale MOF production, leveraging its efficiency, simplicity, and cost-effectiveness. However, its strong dependence on precise reaction conditions warrants a balanced consideration of the two-step method when targeting high-purity or structurally complex MOFs. Ongoing advancements in catalyst design, solvent selection, and process optimization hold promise to further enhance the potential of the one-pot method for large-scale MOF synthesis and PET upcycling applications.

In situ growth of MOFs on PET substrates

Modifying waste PET surfaces to create functional materials is a promising avenue in polymer recycling. MOFs, known for their exceptional properties, have garnered interest across diverse fields.

Directly growing MOFs on PET substrates simplifies synthesis by removing extra processing steps and mitigates issues linked to conventional MOF powders, such as poor recyclability, clogging, and structural degradation^[171–174]. This strategy allows for concurrent material recycling and functional enhancement, broadening the practical applications of MOF-based materials.

The *in situ* growth approach involves chemically functionalizing the PET surface to promote MOF nucleation. For example, PET hydrolysis with NaOH exposes reactive functional groups, facilitating MOF crystallization. However, despite enhancing PET's surface reactivity, the MOF loading remains relatively low^[175,176]. To improve MOF adhesion and loading efficiency, researchers have incorporated surface modifiers such as polyacrylamide (PAM)^[177] and polydopamine (PDA)^[178,179], which provide additional active sites for MOF-substrate interactions and enhance growth performance.

While *in situ* grown MOFs exhibit distinct morphologies compared to their powdered versions, their synthesis methods adhere to either the one-pot or two-step approach. Examples such as UiO-66^[108,177,179,180], MIL-53(Fe)^[181], and MIL-101(Fe)^[142,182] have been successfully incorporated onto PET surfaces using one-pot synthesis. This approach expands MOF application possibilities and significantly improves material reusability.

Mechanical ball milling: a green and efficient approach

Mechanical ball milling has become an eco-friendly and efficient method for converting waste PET into MOFs. Unlike traditional solvothermal techniques, ball milling reduces solvent use, shortens reaction times, and operates under milder conditions^[145,147]. This approach uses mechanical energy to directly transform PET into MOF precursors, thereby cutting production costs and enhancing resource efficiency. The milling of PET facilitates alkaline hydrolysis, yielding Na₂BDC and EG. Na₂BDC then coordinates with metal ions, such as Cu²⁺ and La³⁺, to form MOFs with high surface areas and exceptional catalytic capabilities^[99,146]. Notably, ball milling reduces the dependence on organic solvents, aligning with sustainability objectives^[147].

Mechanical ball milling, although advantageous, encounters issues with MOF loading and crystallinity. The slow degradation rate of PET during milling restricts conversion efficiency, as the mechanical energy might not suffice for complete depolymerization to BDC^[145]. Researchers have tackled this by optimizing milling conditions through multi-step ball milling^[99,146,147] or by adding additives to boost reaction kinetics^[183]. Moreover, integrating ball milling with other synthesis methods has been investigated to enhance crystal morphology and broaden MOF functionalities^[101].

Mechanical ball milling offers a scalable, cost-effective, and environmentally benign approach to PET upcycling and MOF industrialization. Continued progress in energy-efficient processing and reaction optimization will facilitate the broader adoption of this technique for sustainable materials synthesis.

Comparative assessment of PET-to-MOF synthesis strategies

The principal PET-to-MOF routes differ in feed-stock tolerance, process integration, solvent and energy demand, product control, and scale-up readiness. Table 1 summarizes these trade-offs; reported advantages should be interpreted together with purification requirements and application-specific quality targets.

CONVERSION STRATEGIES AND UNIQUE CHALLENGES OF COMPLEX PET WASTE

Market development of waste PET

PET-based materials, commercially known as polyester products, have become predominant in global polymer applications due to their exceptional strength, durability, and cost-effectiveness. Projections indicate that by 2024, polyester-based PET products would account for approximately 70% of the relevant global market, a significant increase from over 50% in 2018. This rapid expansion is primarily driven by growing consumer demand for functional PET-based products and high-performance PET-based substrates, coupled with the widespread application of PET-based materials across diverse polyester-based product sectors. In 2018, global polyester-based PET material production surpassed 55 million tons, constituting over half of the total market. By 2023, production rose to about 71 million tons, capturing 57% of the global

Table 1. Comparative summary of synthesis strategies for PET-derived MOFs

Strategy	Process concept	Advantages	Limitations	Scale-up/cost, solvent and energy	Representative products	Refs.
Two-step	Depolymerize PET; isolate/purify TPA or terephthalate; synthesize MOF	Strong control of linker purity and MOF crystallization; flexible metal selection	Multiple operations; acid/base use; washing and drying; linker losses	Higher separation and utility burden, but conventional unit operations are scalable	UiO-66, MIL-53, MIL-101, Cu-BDC	[34,93,125]
One-pot	PET depolymerization and MOF formation in one reactor	Fewer transfers and shorter flowsheet; may reduce isolation steps	Coupled reaction conditions; impurity sensitivity; less independent control	Potentially lower capital and solvent demand; robust mixing and recovery remain necessary	UiO-66, Cr-BDC MOFs	[156,184]
<i>In situ</i> growth	Grow a MOF directly on PET film, fiber, membrane, or support	Integrates shaping and function; minimizes powder handling	Limited penetration/loading; adhesion and support stability must be controlled	Attractive for roll-to-roll or coated products; substrate preparation adds cost	Ni-MOF/PET and MOF-coated PET composites	[178,185]
Mechanochemical milling	Use milling to promote PET cleavage and metal-linker assembly	Short reaction time; ambient temperature; little or no solvent	Wear, heat removal, mixing uniformity, and continuous solids handling require validation	Low solvent and thermal demand; scale-up depends on mill throughput and quality control	Zn-, Co-, Ni- and mixed-metal terephthalate MOFs	[147]
Microwave-assisted	Use rapid volumetric heating for depolymerization and/or crystallization	Rapid heating; shorter processing time; potential energy savings	Penetration and temperature uniformity become challenging at scale	Promising for intensified processing; equipment and electricity costs require assessment	Terephthalate salts and PET-derived MOFs	[186]
Dual-waste-derived	Recover both organic linker and metal source from separate wastes	Simultaneous valorization; reduced virgin feedstock demand	Variable contaminants; pretreatment and metal speciation control are critical	Potential feedstock savings offset by analytical, purification, and compliance costs	Mixed-metal MIL-88B, Cr-BDC/MIL-101	[154,184,187]

PET: Polyethylene terephthalate; MOFs: metal-organic frameworks; TPA: terephthalic acid.

market share.

The production of rPET materials has expanded in recent years, reaching approximately 8.9 million tons in 2023, which accounts for 12.5% of total polyester-based PET material production. However, the market share of rPET materials has slightly declined, largely due to persistent challenges in sorting, purification, and achieving the quality standards required for high-value applications. Advancements in chemical recycling technologies are poised to drive further growth. By 2030, global polyester-based PET material production is projected to reach 160 million tons, with PET-based materials maintaining market dominance^[188]. The market share of rPET materials is expected to increase as improved recycling strategies overcome technical challenges in processing complex PET-rich waste.

PET has become one of the most widely used con-

densation polymers because of its mechanical robustness, chemical resistance, transparency, processability, and low cost. Beyond conventional bottle-grade PET, large quantities of PET are used in films, trays, containers, labels, multilayer packaging, and other polyester-based products [Figure 5]. The continuous expansion of these application sectors has generated increasingly diverse post-consumer PET-rich waste streams. In contrast to clean laboratory PET or well-sorted bottle flakes, real waste PET feedstocks are rarely compositionally uniform. They may contain clear and colored PET, printed packaging, multilayer structures, contaminated flakes, labels, adhesives, pigments, stabilizers, plasticizers, residual catalysts, organic residues, inorganic impurities, and other polymeric components. This compositional heterogeneity directly increases the difficulty of sorting, depolymerization, monomer recovery, and subsequent high-value conversion^[189,190].

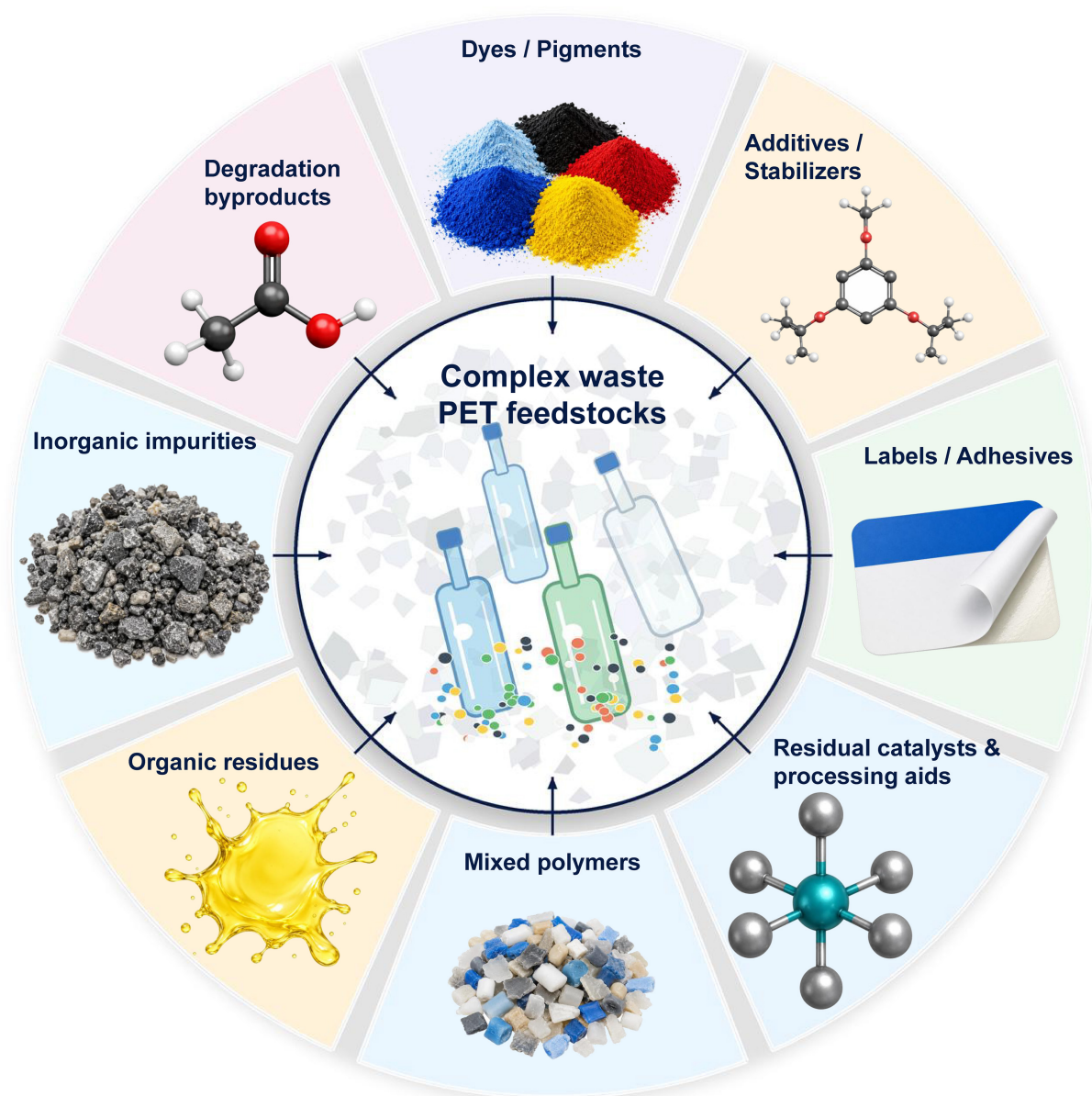


Figure 5. Compositional complexity of real waste PET feedstocks. PET: Polyethylene terephthalate.

The importance of feedstock complexity has been increasingly recognized in plastic recycling research. Mixed polymeric waste streams often exhibit a mismatch between real feedstock heterogeneity and recycling technologies that are optimized for relatively homogeneous polymer inputs^[189]. Even when a waste fraction is enriched in a target polymer, additives, colorants, fillers, residual inorganic species, and secondary polymeric components can alter its conversion behavior. Studies on mixed plastic waste have shown that product distribution and monomer recovery are strongly correlated with feedstock composition and chemical-bond characteristics^[189]. This

insight is highly relevant to PET-derived MOF synthesis, because the quality of recovered TPA, terephthalate salts, or BDC-type linkers is not determined solely by PET content, but also by the accompanying impurity profile and the chemical history of the waste stream.

Despite these challenges, complex PET-rich waste streams also represent an important opportunity for high-value upcycling. The ester backbone of PET enables chemical cleavage and diversification into a broad range of terephthalate-derived intermediates. Recent studies on polyester upcycling emphasize

that post-consumer PET should be treated not merely as waste, but as a resource for producing value-added small molecules, functional monomers, high-performance polymeric materials, and functional composites^[190]. PET-derived TPA and EG are not limited to closed-loop PET production; they can serve as platform chemicals for further valorization. For example, PET-derived TPA has been biologically converted into aromatic and aromatic-derived compounds such as gallic acid, pyrogallol, catechol, muconic acid, and vanillic acid, while EG can be transformed into glycolic acid^[191]. In parallel, waste PET-derived terephthalate salts have been rapidly produced by microwave-assisted processing and further used as organic electrode materials for Li- and Na-ion storage^[186]. These examples demonstrate that PET-derived aromatic dicarboxylate units can be redirected toward value-added chemicals, energy-storage materials, and other advanced functional materials.

For PET-to-MOF conversion, the same principle is particularly important. Recovered TPA, BDC, or terephthalate salts derived from complex PET waste can provide low-cost organic linkers for MOF synthesis; however, dyes, pigments, additives, mixed polymers, inorganic residues, and degradation byproducts may affect linker purity, coordination chemistry, nucleation, crystallization, porosity, morphology, and batch-to-batch reproducibility. Therefore, the utilization of complex PET waste in MOF synthesis should not be regarded simply as replacing commercial BDC with recycled BDC. Instead, it requires a feedstock-aware design strategy that integrates waste sorting, impurity control, linker purification, defect regulation, and application-dependent purity tolerance. From this perspective, complex waste PET feedstocks are both a barrier and a resource: their heterogeneity challenges scalable MOF production, while their abundant terephthalate units provide a sustainable carbon source for high-value porous materials^[186,189-191].

Effect of dye residues and impurity-containing linkers on MOF performance

Residual dyes and associated impurities in PET-derived BDC markedly influence the structural and textural properties of MOFs. Dye contaminants, pigments, and residual additives may be retained during depolymerization and linker recovery, leading to impurity-containing terephthalate linkers that affect

MOF crystallization, defect formation, pore accessibility, and consequently adsorption or catalytic performance. For instance, UiO-66 synthesized from colored PET-derived BDC exhibited specific surface areas of 933–1,085 m²·g⁻¹, which were significantly lower than that of UiO-66 synthesized from commercial BDC (1,368 m²·g⁻¹)^[34]. Alkaline hydrolysis of dye-containing PET-rich waste produces regenerated terephthalic acid (rTPA) in which residual dye impurities may remain even after repeated washing, affecting the purity, optical appearance, and subsequent usability of the recovered linker [Figure 6A and B]^[192]. Consequently, processing colored or compositionally complex PET waste generally requires additional decolorization, separation, or purification steps, affecting scalability and economic viability^[193].

Thermogravimetric analysis and nitrogen adsorption measurements further reveal the influence of impurity-containing linkers on PET-derived MOFs. UiO-66 synthesized from colored PET waste may exhibit altered multi-stage thermal decomposition behavior and reduced nitrogen adsorption capacity, indicating changes in thermal stability, pore structure, and accessible surface area [Figure 6D and E]^[34]. Incomplete dye removal can therefore modify framework porosity, thermal stability, and adsorption behavior. These results underscore the importance of effective dye-removal and impurity-control strategies for maintaining the structural quality and functional performance of PET-derived MOFs.

Advances in decolorization, purification, and impurity-control technologies

Recent advances in addressing dye-residue challenges have led to the development of various decolorization and separation techniques. Among these, microwave-assisted alcoholysis has proven effective, facilitating the rapid depolymerization of dye-containing PET-rich waste and the separation of PET-derived monomers from non-PET components. Utilizing a ZnO catalyst, efficient PET depolymerization can be achieved within 15 min, with dyes successfully extracted into the solution^[10]. Further treatment with HCl has been shown to remove dye and additive or surface-treatment residues, enhancing the purity of recovered BDC^[194].

Beyond direct chemical treatments, integrated synthesis strategies have been devised to address dye-relat-

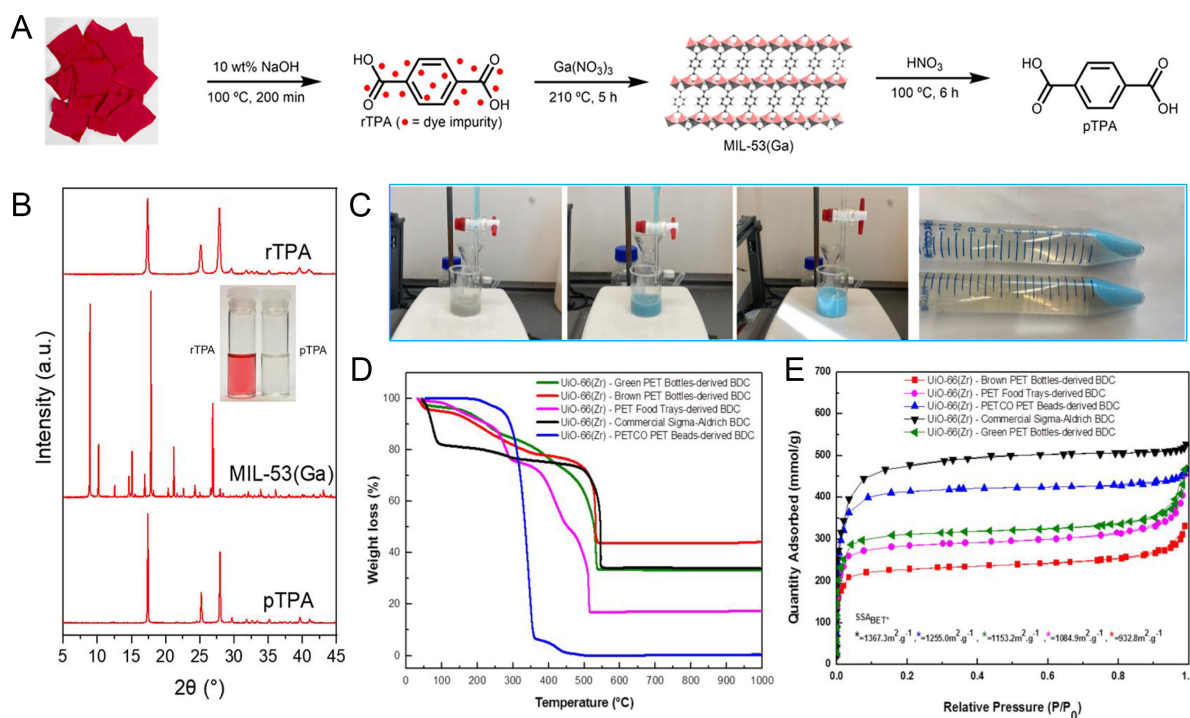


Figure 6. (A) Schematic illustration of the steps used to recover TPA from complex PET-rich waste. rTPA and pTPA denote recycled terephthalic acid and purified terephthalic acid, respectively; (B) Powder X-ray diffraction patterns of rTPA recovered from a red mixed PET/non-PET feedstock, MIL-53(Ga) synthesized from rTPA, and pTPA obtained from MOF disassembly. Inset: photographs of rTPA and pTPA in DMSO. (A and B) are adapted with permission from reference^[192]. Copyright 2023, American Chemical Society; (C) Photographs of the room-temperature synthesis of CuBDC MOFs using Na₂BDC obtained from depolymerized blue-dye polyester. (C) is adapted with permission from reference^[132]. Copyright 2023, American Chemical Society; (D) Thermogravimetric analysis curves and (E) N₂ sorption isotherms of UiO-66(Zr) samples prepared from different BDC sources. (D and E) are adapted with permission from reference^[34]. Copyright 2019, American Chemical Society. TPA: Terephthalic acid; rTPA: recycled TPA; pTPA: purified TPA; PET: polyethylene terephthalate; MOFs: metal-organic frameworks; DMSO: dimethyl sulfoxide.

ed issues in MOF formation. A notable example is a two-step synthesis method used to create Cu-MOFs from dye-containing PET-derived precursors, where dye removal coincides with MOF crystallization. Research indicates that dye residue effects on MOF properties depend on the dye's molecular size and its interaction with MOF precursors. Larger dye molecules may be sterically excluded from MOF pores or interact weakly with MOF precursors, whereas smaller or coordinating dye molecules may interfere more strongly with nucleation, pore formation, and framework growth [Figure 6C]^[132,195]. In addition, acid hydrolysis combined with template-assisted growth can convert PET-derived linkers into UiO-66-based composites under controlled conditions, demonstrating the potential of rPET precursors for constructing functional MOF-containing materials^[108,196,197]. However, this type of strategy should be discussed in terms of linker recovery, framework growth, and composite formation, rather than as a substrate-preservation route.

Despite advancements, current decolorization and separation methods face limitations such as high energy consumption, substantial reagent use, and reliance on organic solvents. Recent research addresses these challenges by introducing an all-aqueous reaction crystallization technique. This method efficiently removes dyes and synthesizes Zn-MOFs using only metal salts and water, eliminating the need for alkaline conditions or organic solvents^[198]. This all-aqueous strategy offers a greener route for converting dye-containing PET-derived precursors into MOFs. Nonetheless, further optimization is required to enhance efficiency, scalability, and cost-effectiveness, ensuring viability for large-scale applications. Future research should prioritize developing selective separation techniques, refining reaction conditions, and investigating enzymatic degradation methods to bolster the sustainability of complex PET waste-to-MOF conversion.

APPLICATIONS OF PET-DERIVED MOFS

Environmental remediation and protection

Gas adsorption and storage

MOFs synthesized from waste PET show significant promise for CO₂ adsorption and separation. Given that CO₂ is a major industrial greenhouse gas contributing to climate change, advancing efficient CO₂ capture technologies is crucial. Owing to their high specific surface area and customizable organic functionalities, MOFs have emerged as a focal point in gas adsorption and separation research^[199,200]. Recent progress in industrial MOF-based carbon capture, such as the scale-up of CALF-20 for post-combustion CO₂ capture, further highlights the practical relevance of stable and cost-effective MOF adsorbents, although such systems are not derived from PET waste^[201]. For example, MIL-53(Al) synthesized using BDC ligands extracted from waste PET exhibits a CO₂ adsorption capacity of 3.67 mmol·g⁻¹, comparable to that of commercial MIL-53(Al) (3.89 mmol·g⁻¹), while its production cost is only one-third of the latter. The synthesis employs recycled aluminum from food packaging, such as foil and cans, as the aluminum source, thereby enhancing the sustainability of the process^[124]. This green methodology not only reduces production costs but also minimizes the overall carbon footprint. More recently, Choi *et al.* reported synthesizing MIL-53(Al)-R using TPA recovered by acidic hydrolysis of post-consumer PET waste. The resulting MIL-53(Al)-R showed comparable crystal structure, morphology, porosity, and gas adsorption behavior to MIL-53(Al)-C synthesized from commercial TPA, confirming the feasibility of using rPET-derived TPA as a reliable linker source for gas separation and storage applications [Figure 7]^[202]. PET-derived MOFs demonstrate significant potential for clean-energy gas storage. Specifically, Cr-MOF and UiO-66 offer exceptional thermal and humidity stability, rendering them effective for hydrogen storage with adsorption capacities of 2.1 and 1.2 wt%, respectively^[90,203]. The Cr-MOF derived from PET exhibits superior textural characteristics and hydrogen storage efficiency compared to commercially available BDC-based MOFs. This is attributed to its exceptionally high pore volume, extensive surface area, and numerous unsaturated chromium active sites. However, while these materials demonstrate promising performance, they remain at the laboratory research stage and have not yet been industrial-

ized.

Another representative example is MOF-5, which possesses a CO₂ adsorption capacity ranging from 1.12 to 1.50 mmol·g⁻¹^[204,205], but its poor moisture stability constrains practical applications^[206,207]. To address this limitation, Rocha *et al.* optimized the extraction of BDC ligands from waste PET, synthesizing MOF-5 with enhanced crystallinity and structural stability^[115]. The resulting material demonstrated an improved CO₂ adsorption capacity of 2.5 mmol·g⁻¹ and retained 80% of its adsorption performance after 24 h of moisture exposure. UiO-66 is notable among industrial-grade CO₂ adsorbents for its exceptional thermal, mechanical, and chemical stability^[208,209]. Synthesized with BDC ligands from waste PET, UiO-66 develops significant structural defects, enhancing its surface area and porosity. Consequently, it achieves a CO₂ adsorption capacity of 2.06 mmol·g⁻¹, positioning it as a promising option for efficient carbon capture^[156]. Overall, these studies show that PET-derived MOFs can achieve gas adsorption performance comparable to commercial linker-derived analogs while reducing dependence on virgin petrochemical linkers and supporting circular material design^[202].

Separation

Separating complex gas mixtures is another promising application of MOFs. For instance, Zhou *et al.* synthesized a Zr₁₂-cluster MOF (hcp UiO-66) derived from waste PET, which exhibited exceptional selectivity in the separation of cyclohexane and benzene^[158]. The material's exceptional performance is attributed to its pore size (~6.0 Å), which closely matches the kinetic diameters of cyclohexane and benzene, enabling a molecular sieving effect^[158,210]. This selective adsorption capacity is environmentally relevant, as it extends beyond greenhouse gases to the capture and removal of volatile organic compounds (VOCs). Compounds such as toluene, which pose serious risks to air quality and human health, particularly in confined spaces, can be effectively mitigated through this adsorption process^[211-213]. MOFs demonstrate enhanced VOC adsorption compared to traditional materials such as activated carbon and zeolites, largely due to robust π - π and cation- π interactions. Notably, MIL-101(Cr) synthesized from waste PET achieves a toluene adsorption capacity of 40.3 mmol·g⁻¹, closely matching the 42.2 mmol·g⁻¹ of

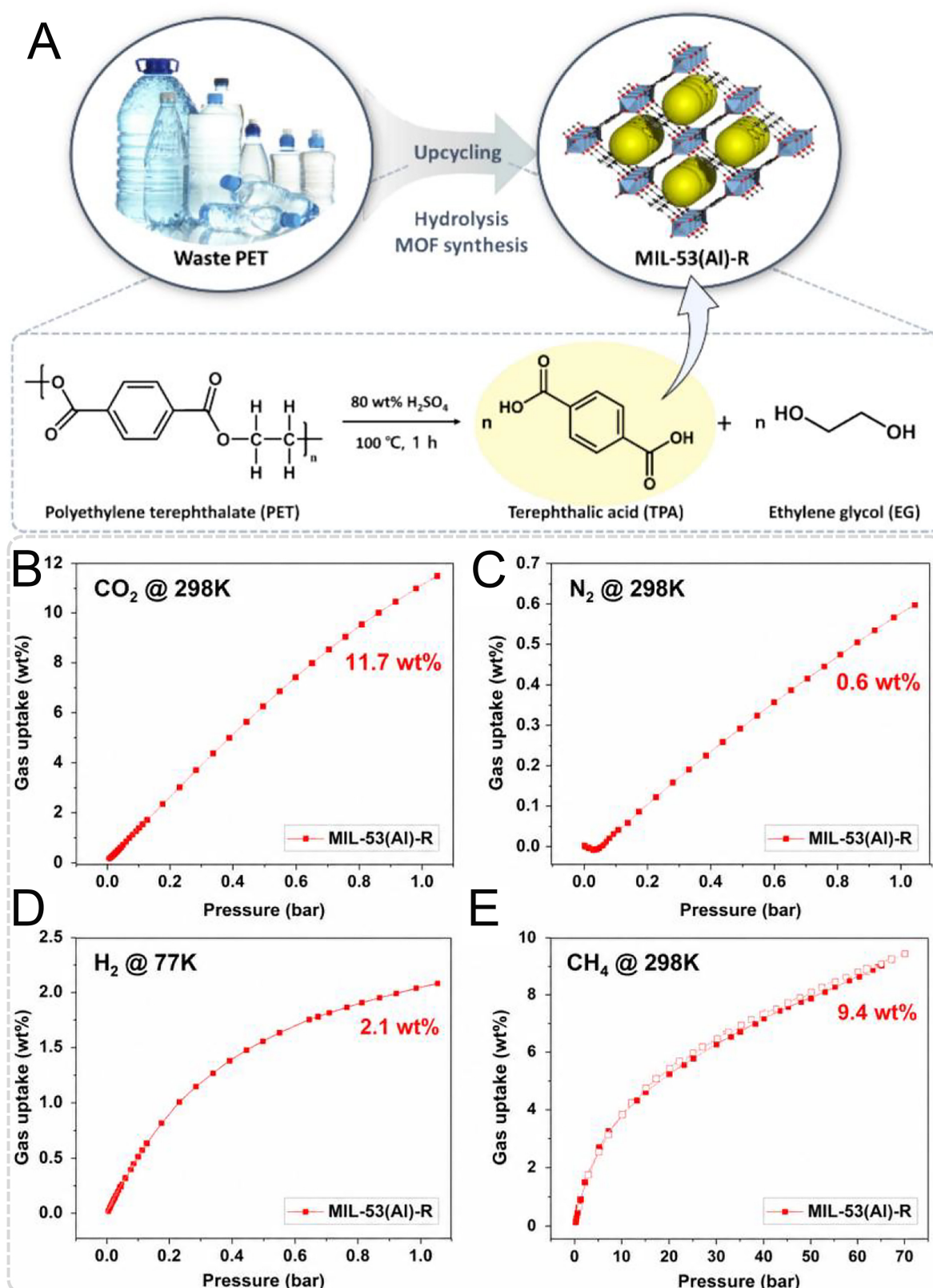


Figure 7. PET-derived MIL-53(Al)-R for gas adsorption. (A) Eco-friendly synthesis procedure of MIL-53(Al)-R from waste PET depolymerization. Gas adsorption isotherms of MIL-53(Al)-R for (B) CO₂ at 298 K, (C) N₂ at 298 K, (D) H₂ at 77 K, and (E) CH₄ at 298 K. All panels are adapted from reference^[202] under the terms of the Creative Commons Attribution 4.0 International license. Copyright 2025, The Author(s). PET: Polyethylene terephthalate.

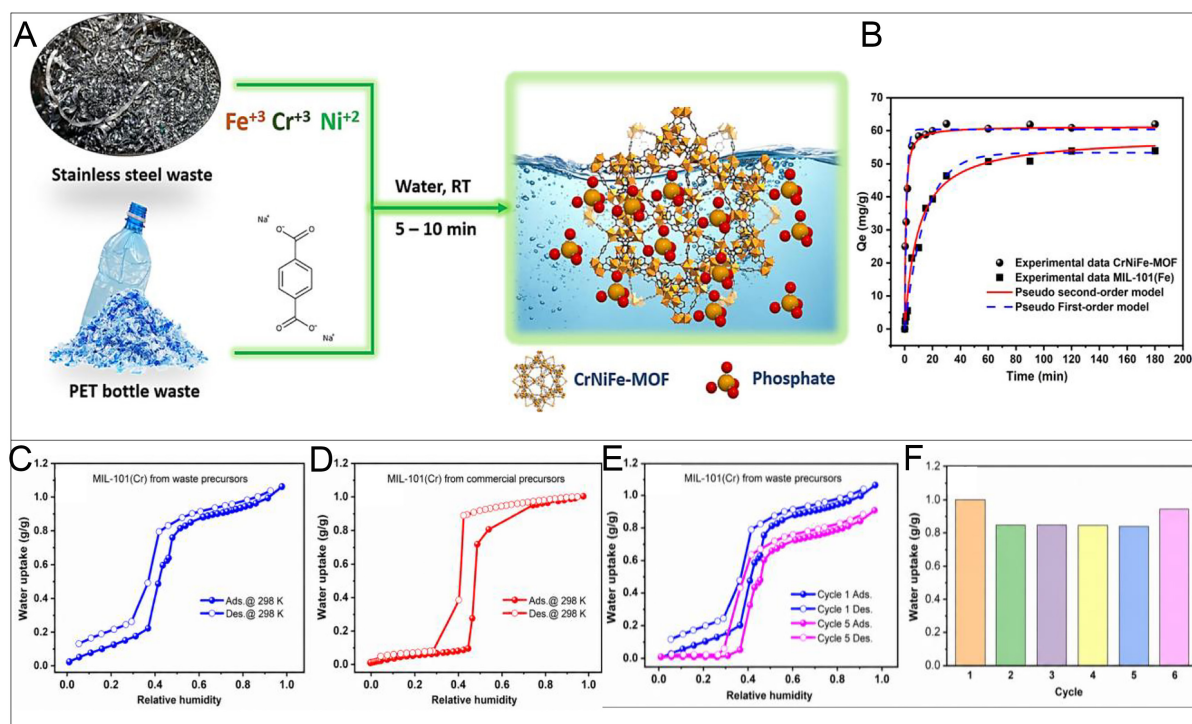


Figure 8. Representative dual-waste-derived MOFs for water-related adsorption applications. (A) Sustainable upcycling of stainless-steel waste and PET-derived disodium terephthalate into a Cr-Ni-Fe-based MOF for phosphate removal from water; (B) Effect of adsorption time on phosphate uptake from aqueous solutions using MIL-101(Fe) and CrNiFe-MOF ([P] = 10 mg L⁻¹; adsorbent = 20 mg; V = 50 mL; T = 293 K); (C and D) H₂O adsorption isotherms collected at 298 K for waste-derived and commercial precursor-based MIL-101(Cr) MOFs, respectively; (E and F) Cyclic water adsorption isotherms for the 1st and 5th cycles and water uptake at 90% relative humidity for waste-derived MIL-101(Cr). (A and B) are adapted with permission from reference^[187]. Copyright 2024, American Chemical Society. (C-F) are adapted from reference^[184] under the terms of the Creative Commons Attribution 4.0 International license. Copyright 2025, The Author(s). MOFs: Metal-organic frameworks; PET: polyethylene terephthalate; RT: room temperature.

its commercial BDC-derived counterpart, suggesting that the green synthesis method maintains adsorption efficacy^[161,214,215]. Fe-based MOFs demonstrate exceptional adsorption efficiency for aromatic VOCs through the synergistic effects of π - π interactions and hydrogen bonding between the benzene rings in their framework and the target VOCs^[216]. In a recent study, Chen *et al.*^[182] synthesized MIL-101(Fe) using waste PET as the organic linker, achieving maximum adsorption capacities of 68.72, 91.63, and 78.47 mg·g⁻¹ for benzene, toluene, and m-xylene, respectively. These results underscore the promising potential of PET-derived MOFs for effective VOC removal applications.

Water treatment and pollutant removal

The escalation of global water pollution, characterized by industrial wastewater laden with organic dyes, heavy metals, pesticides, and pharmaceutical residues, poses serious risks to ecosystems and human health^[87,135]. MOFs, with their high specific surface area, adjustable porous structures, and superi-

or adsorption capabilities, offer notable benefits for water purification. Recent research highlights their potential to adsorb and remove plastic nanoparticles like polymethyl methacrylate (PMMA) and polyvinyl chloride (PVC), broadening their applicability in managing emerging pollutants^[98]. Recent studies further indicate that PET-derived MOFs are being extended from conventional dye adsorption toward heavy-metal capture and pesticide-contaminated water treatment, demonstrating the growing application scope of waste-derived MOFs in aqueous remediation^[119,217-219]. More importantly, recent studies have moved beyond single-waste PET valorization by combining PET-derived terephthalate linkers with metal sources recovered from inorganic or industrial wastes, thereby enabling dual-waste-derived MOFs for phosphate removal and water-sorption-related applications [Figure 8]^[184,187].

MOFs effectively remove organic dyes through electrostatic interactions, hydrogen bonding, and π - π

stacking^[220–225]. Structural modifications are often necessary to improve selectivity for specific dyes. Amino-functionalized MIL-101(Cr) significantly enhances methylene blue (MB) adsorption through hydrogen bonding and electrostatic interactions^[118]. To reduce environmental and safety concerns associated with HF, HF-free synthesis methods have been introduced for MIL-101(Cr)^[138]. MIL-101(Cr) synthesized without HF maintains excellent adsorption capacities, achieving 662.87 mg·g⁻¹ for RR2 and 863.67 mg·g⁻¹ for RB19^[119], while another MIL-101(Cr) system showed a maximum adsorption capacity of 2,176 mg·g⁻¹ for AB-92^[121]. These results indicate that HF is not indispensable for achieving high dye-adsorption performance in MIL-101(Cr)-based systems^[119,121]. More recently, Ngo *et al.* converted PET plastic into MOF materials for organic dye adsorption, further confirming that PET-derived linkers can be used to construct efficient dye adsorbents for water purification^[217]. Cheng *et al.* also reported waste PET-derived MIL-101(Cr) for the efficient adsorption and removal of anionic dyes, providing a 2025 example that directly strengthens the anionic dye-removal subsection^[119]. Beyond dye adsorption, MOF-based adsorbents have also been reported for toxic metal-ion removal from acid rock drainage, further supporting their relevance to water-remediation applications^[226]. Additionally, Cr-based MOFs demonstrate reduced toxicity, underscoring their environmental benefits in practical applications^[227,228]. Similarly, Ca-MOF is a low-toxicity option that can function effectively under non-acidic conditions and has been synthesized for the removal of Alizarin Red S dye, achieving an adsorption capacity of 979.0 mg·g⁻¹^[85].

MOFs have also demonstrated strong adsorption capacities for pharmaceutical and pesticide residues, particularly in antibiotic degradation^[229–232]. MOF-5 synthesized from waste PET exhibits a maximum tetracycline (TC) adsorption capacity of 2,325.55 mg·g⁻¹, attributed to hydrogen bonding and ionic interactions between MOF frameworks and TC's unsaturated bonds^[92,229,233]. Moreover, UiO-66, with its high porosity and thermal stability, efficiently adsorbs the nonsteroidal anti-inflammatory drug ketorolac tromethamine (KTC) under acidic conditions, with an adsorption capacity of 729.92 mg·g⁻¹^[130]. By introducing defects, UiO-66 achieves enhanced pore structures and more exposed metal active sites, significantly improving

its adsorption efficiency for lomefloxacin^[129].

Neonicotinoid pesticides, such as imidacloprid, pose significant ecological threats^[234–236]. To address this issue, several MOFs, including MIL-101(Cr)-NH₂^[237], MIL-101(Fe)^[238], and UiO-66^[239], have been developed to remove imidacloprid. Notably, UiO-66 derived from PET exhibits remarkable efficiency in capturing imidacloprid, with enhanced permeability further improving its adsorption performance^[179]. Compared to commercially available MOFs, the superior permeability of PET-derived UiO-66 enables more effective adsorption and removal of imidacloprid. A recent study further extended this direction by using a PET-derived MIL-53(Al)/PMMA nanofiber-incorporated poly(vinylidene fluoride) (PVDF) membrane for removing hazardous pesticides, including atrazine and chlorpyrifos, demonstrating the potential of PET-derived MOF-based membranes for agricultural runoff treatment^[219]. MOFs have emerged as promising adsorbents for removing oxygen-containing anionic pollutants, such as phosphates and arsenates, which significantly impact water quality and soil health^[240]. Notably, Fe- and Zr-based MOFs have demonstrated adsorption capacities of 72.16 mg·g⁻¹ and 66.63 mg·g⁻¹ for phosphate at pH 6.5, respectively^[96]. By optimizing surface charge properties, Sn(II)-MOF further enhances adsorption, achieving capacities of 90.90 mg·g⁻¹ and 126.58 mg·g⁻¹ for arsenate and phosphate, respectively, under acidic conditions^[93]. A more recent example is the ultrarapid synthesis of a trimetallic CrNiFe-MOF from stainless-steel waste and disodium terephthalate derived from PET waste [Figure 8A]^[187]. This strategy is particularly significant because both the organic linker and metal nodes originate from waste streams, while the MOF can be produced in water at room temperature within only 5–10 min. As shown in Figure 8B, CrNiFe-MOF displayed faster phosphate uptake than MIL-101(Fe), reaching 61.40 mg·g⁻¹ within the first 10 min and a maximum phosphate adsorption capacity of 179.97 mg·g⁻¹. The enhanced performance was attributed to the stronger phosphate affinity of Cr-containing oxo-trimer sites and possible defect/mesoporosity contributions, demonstrating that multi-metallic waste-derived MOFs can provide both sustainable synthesis and efficient oxyanion removal.

MOFs synthesized using BDC ligands derived from rPET bottles have shown promising adsorption capabilities for removing arsenate and perfluorooctanoic acid (PFOA) from aqueous environments. Specifically, La-MOF exhibits an arsenate adsorption capacity of $114.28 \text{ mg}\cdot\text{g}^{-1}$ at pH 7, while La-MOF and Zr-MOF achieve PFOA adsorption capacities of $310 \text{ mg}\cdot\text{g}^{-1}$ and $290 \text{ mg}\cdot\text{g}^{-1}$, respectively^[241,242]. The superior adsorptive capacity of La-MOF has been attributed to its slower permeation rate and extended adsorption activity^[241]. Similarly, Ba-MOF^[137] and MIL-101(Al)^[123] have been effectively employed to remove sulfate and orthophosphate. In addition to liquid-phase pollutant adsorption, waste-derived Cr-BDC MOFs have also been explored for water-sorption-related applications. Delhali *et al.* synthesized MIL-101(Cr) and MIL-53(Cr) by combining Cr(III) recovered from tannery effluent with TPA obtained from waste PET bottles^[184]. The H_2O adsorption isotherms show that waste-derived MIL-101(Cr) exhibits a sigmoidal water adsorption profile comparable to that of its commercial precursor-based counterpart, confirming that waste-derived precursors can preserve the intrinsic water-sorption behavior of MIL-101(Cr) [Figure 8C and D]. Moreover, the cyclic water adsorption isotherms and water uptake at 90% relative humidity demonstrate stable adsorption-desorption performance over repeated cycles [Figure 8E and F], highlighting the potential of dual-waste-derived Cr-MOFs for humidity control, water harvesting, and adsorption-based water-management applications.

MOFs have demonstrated remarkable potential for the removal of heavy metal pollutants. For instance, a Ca-based MOF has been reported to achieve removal efficiencies of 98.99% and 99.18% for U(VI) and Th(IV) ions, respectively, at pH 5^[243,244]. This high performance can be attributed to the biocompatibility of the Ca ions, which helps minimize the risk of secondary environmental pollution. Kumar *et al.* reported an efficient and economical approach to synthesize Ca-MOF using waste eggshells as a Ca^{2+} source and waste plastics as an organic ligand^[134]. The resulting material effectively removed Pb^{2+} , Cd^{2+} , and Cu^{2+} from wastewater, with maximum adsorption capacities of 644.07 ± 47 , 391.4 ± 26 , and $260.5 \pm 14 \text{ mg}\cdot\text{g}^{-1}$, respectively. More recently, Kim *et al.* developed a waste PET-derived MOF-grafted polyaniline (PANI) composite for

heavy-metal adsorption from aqueous solution, providing a 2025 example of composite engineering to improve the practical performance of PET-derived MOF adsorbents^[218].

Researchers have investigated MOF growth on flexible substrates to boost practical applicability. UiO-66- NH_2 synthesized on PET-based polymer substrates yielded a flexible MOF-coated material with a Pb(II) adsorption capacity of $711.99 \text{ mg}\cdot\text{g}^{-1}$ ^[177]. This enhancement is due to the improved thermal stability and increased surface area of aminated UiO-66, underscoring the potential of MOF-functionalized polymer substrates for large-scale water purification^[245].

Collectively, PET-derived MOFs show significant promise in environmental remediation, especially for removing persistent organic pollutants [Table 2]. Their high surface area, adjustable porosity, and varied active sites enhance their catalytic efficiency, while their structural stability across different environmental conditions supports long-term performance. These characteristics make PET-derived MOFs strong contenders for sustainable and scalable water remediation technologies.

Energy storage and conversion

MOFs in energy storage and conversion have garnered substantial research interest in recent years. Particularly, MOFs derived from PET have emerged as promising materials, owing to their exceptional physicochemical characteristics. These PET-based MOFs have demonstrated remarkable potential in various energy-related applications, including gas storage, electrochemical energy storage, thermal energy storage, and energy conversion processes, thereby providing sustainable alternatives for clean energy technologies.

Electrochemical energy storage

The utilization of PET-derived MOFs as electrode materials in lithium-ion batteries (LIBs) has garnered significant attention owing to their tailorable porosity, high specific surface area, and environmentally benign synthetic protocols. The seminal work by Tarascon and colleagues in 2009 showcased the viability of MIL-53(Fe) as an anode material for LIBs through a conversion reaction mechanism^[251]. Since then, PET-derived MOFs have been regarded

Table 2. PET-derived MOFs for environmental remediation, adsorption, and separation

Adsorbates	Properties	Two-step method			MOFs	Year	Ref.
		Hydrolysis method of waste PET	Synthesis method of PET-derived MOFs	Synthesis conditions			
Ketorolac tromethamine	$Q_{\max} = 729.92 \text{ mg}\cdot\text{g}^{-1}$	Alkaline hydrolysis	Solvothermal	150 °C, 4 h	UiO-66	2018	[130]
Arsenate ₍₁₎ Phosphate ₍₂₎	$Q_1 = 90.90 \text{ mg}\cdot\text{g}^{-1}$ $Q_2 = 126.58 \text{ mg}\cdot\text{g}^{-1}$	Glycolysis	Solvothermal	170 °C, 24 h	Sn(II)-MOF	2021	[93]
Methylene blue	$Q_{\max} = 41.01 \text{ mg}\cdot\text{g}^{-1}$	Alkaline hydrolysis	Solvothermal	100 °C, 24 h	Cu-MOF	2020	[86]
Pollutant adsorption		Ultrasound-assisted alkaline hydrolysis	Solvothermal	150 °C, 15 h	Fe-MOF	2020	[87]
CO ₂	$Q = 3.67 \text{ mmol}\cdot\text{g}^{-1}$ (16 wt%)	Glycolysis (Bottles and foil/cans)	Hydrothermal	220 °C, 72 h	MIL-53(Al)	2020	[124]
Sulfate	$Q_{\max} = 549.5 \text{ mg}\cdot\text{g}^{-1}$	Acid hydrolysis	Hydrothermal	500 rpm, 24 h	Ba-MOF	2022	[137]
Eriochrome Black T	Removal ~77% (90 min)	Microwave-assisted alkaline hydrolysis	Hydrothermal		Al-MOF	2022	[246]
CO ₂	$Q_{\text{atm}} = 2.5 \text{ mmol}\cdot\text{g}^{-1}$	Alkaline hydrolysis	Solvothermal	100 °C, 7 h	MOF-5	2022	[115]
Alizarin red S	$Q = 979.0 \text{ mg}\cdot\text{g}^{-1}$	Acid hydrolysis (H ₂ SO ₄)	Solvothermal	125 °C, 84 h	Ca-MOF	2022	[85]
Cu(II)	$Q_{\max} = 358.3 \text{ mg}\cdot\text{g}^{-1}$	Acid hydrolysis (H ₂ SO ₄)	Solvothermal	125 °C, 84 h	Ca-MOF	2022	[135]
Water adsorption		Alkaline hydrolysis	Hydrothermal	180 °C, 72 h	Cr-MOF	2023	[184]
Pollutant adsorption		Acid hydrolysis (HNO ₃)	Solvothermal	60 °C, 24 h	Cu-MOF	2023	[95]
Phosphate	$Q = 826 \text{ mg}\cdot\text{g}^{-1}$	Alkaline hydrolysis	Hydrothermal	450 rpm, 24 h	MIL-53(Al)	2024	[123]
Plastic Nanoparticles	Removal 83%-85%	Alkaline hydrolysis	Solvothermal	120 °C, 24 h	MOF-5	2024	[98]
Pollutant adsorption		Alkaline hydrolysis	Solvothermal	125 °C, 48 h	Ca-MOF	2024	[134]
Phosphate	$Q = 72.16 \text{ mg}\cdot\text{g}^{-1}$	Alkaline hydrolysis	Hydrothermal	110 °C, 24 h; 120 °C, 24 h; 220 °C, 72 h	Fe, Zr, Al-MOF	2024	[96]
Th(IV); U(VI)	$Q_{\max} = 829.18 \text{ mg}\cdot\text{g}^{-1}$ $Q_{\max} = 273.16 \text{ mg}\cdot\text{g}^{-1}$	Glycolysis	Hydrothermal	150 °C, 24 h	Ca-MOF	2024	[243]
Acid Blue 92	$Q_{\max} = 2,176 \text{ mg}\cdot\text{g}^{-1}$	Alkaline hydrolysis	Hydrothermal	220 °C, 12 h	MIL-101(Cr)	2024	[121]
Lomefloxacin	$Q = 588 \text{ mg}\cdot\text{g}^{-1}$	Alkaline hydrolysis	Grinding + baking	120 °C, 6 h	UiO-66	2024	[129]
Reactive Red 2 ₍₁₎ Reactive Blue 19 ₍₂₎	$Q_{\text{avg}1} = 662.87 \text{ mg}\cdot\text{g}^{-1}$, $Q_{\text{avg}2} = 863.67 \text{ mg}\cdot\text{g}^{-1}$	Glycolysis	Hydrothermal	220 °C, 12 h	MIL-101(Cr)	2025	[119]
TCH		Alkaline hydrolysis		25 °C, 1 h	MIL-88B(Fe)	2025	[247]
MB		Alkaline hydrolysis	Ball Milling + Microwave Reactor	120 °C, 30 min	Na-MOF	2025	[248]
Application	Properties	One-pot synthesis			MOFs	Year	Ref.
		Synthesis method of PET-derived MOFs		Synthesis conditions			
Benzene ₍₁₎ Cyclohexane ₍₂₎	$Q_1 = 4.96 \text{ mmol}\cdot\text{g}^{-1}$, $Q_2 = 2.19 \text{ mmol}\cdot\text{g}^{-1}$	Hydrothermal		160 °C, 12, 18, 24, 30 and 36 h	UiO-66(Zr)	2019	[158]
Methylene blue	Removal 91.7%	Hydrothermal		210 °C, 8 h	MIL-101(Cr)	2021	[118]
Diclofenac sodium	Removal 92.94% ± 0.47%	Hydrothermal		220 °C, 72 h	MIL-53(Al)	2021	[249]

Pollutant adsorption	$Q_{\max(1)} = 70.02$ $\text{mg}\cdot\text{g}^{-1}$, $Q_{\max(2)} = 85.72$ $\text{mg}\cdot\text{g}^{-1}$, $Q_{\max(3)} = 114.28$ $\text{mg}\cdot\text{g}^{-1}$	Solvothermal	160 °C, 12 h	$\text{Fe}_{(1)}$, $\text{Zr}_{(2)}$, $\text{La}_{(3)}$ -MOF	2022	[241]
Zr(IV)	$Q = 113.0$ $\text{mg}\cdot\text{g}^{-1}$	Hydrothermal	220 °C, 24 h	MIL-88B	2023	[154]
Pollutant adsorption	$Q_{\max(1)} = 310$ $\text{mg}\cdot\text{g}^{-1}$, $Q_{\max(2)} = 290$ $\text{mg}\cdot\text{g}^{-1}$	Microwave-assisted solvothermal	160 °C, 45 min	La-MOF ₍₁₎ , Zr-MOF ₍₂₎	2023	[242]
CO ₂	$Q = 2.06$ $\text{mmol}\cdot\text{g}^{-1}$	Microwave-assisted solvothermal	200 °C, 30 min	UiO-66	2023	[156]
Tetracycline	$Q_{\max} = 2,325.55$ $\text{mg}\cdot\text{g}^{-1}$	Hydrothermal	210 °C, 8 h	MOF-5	2024	[92]
Congo red (1 g·L ⁻¹), acetone	$Q_{\max} = 2,312$ $\text{mg}\cdot\text{g}^{-1}$ (2h), Acetone: LOD = 0.048% (v/v)	Solvothermal	180 °C, 48 h	Eu-MOF	2024	[250]
In situ growth						
Adsorbates	Properties	Support	Synthesis method of PET-derived MOFs	MOFs	Year	Ref.
Pb(II)	$Q_{\max} = 711.99$ $\text{mg}\cdot\text{g}^{-1}$	PET	Solvothermal	UiO-66	2020	[177]
Pollutant adsorption		PET	Solvothermal	UiO-66	2021	[179]
ASA ₍₁₎ , ROX ₍₂₎ , As(V) ₍₃₎	$Q_{\max(1)} = 320.6$ $\text{mg}\cdot\text{g}^{-1}$, $Q_{\max(2)} = 476.5$ $\text{mg}\cdot\text{g}^{-1}$, $Q_{\max(3)} = 240.0$ $\text{mg}\cdot\text{g}^{-1}$	PET	Solvothermal	MIL-101(Fe)	2024	[142]

Q , $Q_{\max}$, and Q_{avg} : Adsorption capacity, maximum adsorption capacity and average adsorption capacity, respectively; LOD: detection limit; ASA: 4-aminophenylarsonic acid; ROX: hydroxy-3-nitrobenzenearsonic acid; MOFs: metal-organic frameworks; PET: polyethylene terephthalate.

as promising anode candidates for LIBs. Notably, Ca-MOF and Ba-MOF, synthesized from the abundant elements calcium and barium, demonstrate exceptional electrochemical performance. After 100 charge/discharge cycles, Ca-MOF and Ba-MOF achieve specific capacities of 403 and 167 $\text{mAh}\cdot\text{g}^{-1}$, respectively^[107]. The choice of metal centers in MOFs is a critical factor influencing their lithium storage capabilities^[252]. Co-based MOFs, for instance, enable efficient electron transport owing to their accessible redox states (+1 to +4), rendering them highly promising for advanced energy storage technologies. Metal-ion doping significantly enhances electrochemical performance by boosting conductivity. PET-derived Co/Ni-MOF and Co/Zn-MOF, created through bimetallic doping, demonstrate exceptional lithium storage capabilities. Co/Ni-MOF shows initial discharge/charge capacities of 2,496 and 1,729 $\text{mAh}\cdot\text{g}^{-1}$, respectively, maintaining a Coulombic efficiency above 99% after 200 cycles. Similarly, Co/Zn-MOF achieves a first-cycle discharge/charge capacity of 2,774/1,971 $\text{mAh}\cdot\text{g}^{-1}$, with a Coulombic efficiency of 71%, markedly surpassing single-metal Co-MOF [Figure 9]^[102,103].

Porous MOFs derived from PET have been extensively investigated as electrode materials for supercapacitors. Their high specific surface areas and hierarchical micro-/mesoporous structures provide ideal conditions for charge storage and rapid charge-discharge kinetics^[253-255]. For instance, Cu-, Zr-, and Ti-based MOFs synthesized by Dubey^[133] exhibit Brunauer-Emmett-Teller (BET) surface areas of 1,321, 720, and 574 $\text{m}^2\cdot\text{g}^{-1}$, respectively. Among these, the Cu-MOF exhibits superior electrochemical performance, achieving a specific capacitance of 104.8 $\text{F}\cdot\text{g}^{-1}$ at a current density of 0.5 $\text{A}\cdot\text{g}^{-1}$ in a three-electrode system, attributed to its high surface area and efficient ion transport properties. Carbonized MOFs can be converted into conductive materials like porous and graphitized carbon, boosting conductivity and electrochemical stability^[117,256,257]. For instance, PET-derived Ni-MOF, once carbonized, offers a surface area of 1,523 $\text{m}^2\cdot\text{g}^{-1}$ with enhanced mesopores (11–13 nm), achieving a specific capacitance of 581.30 $\text{F}\cdot\text{g}^{-1}$ at a scan rate of 5 $\text{mV}\cdot\text{s}^{-1}$ ^[104]. Additionally, doping with heteroatoms such as boron, nitrogen, sulfur, and phosphorus further improves electron and ion transport, optimizing supercapacitor performance^[258,259].

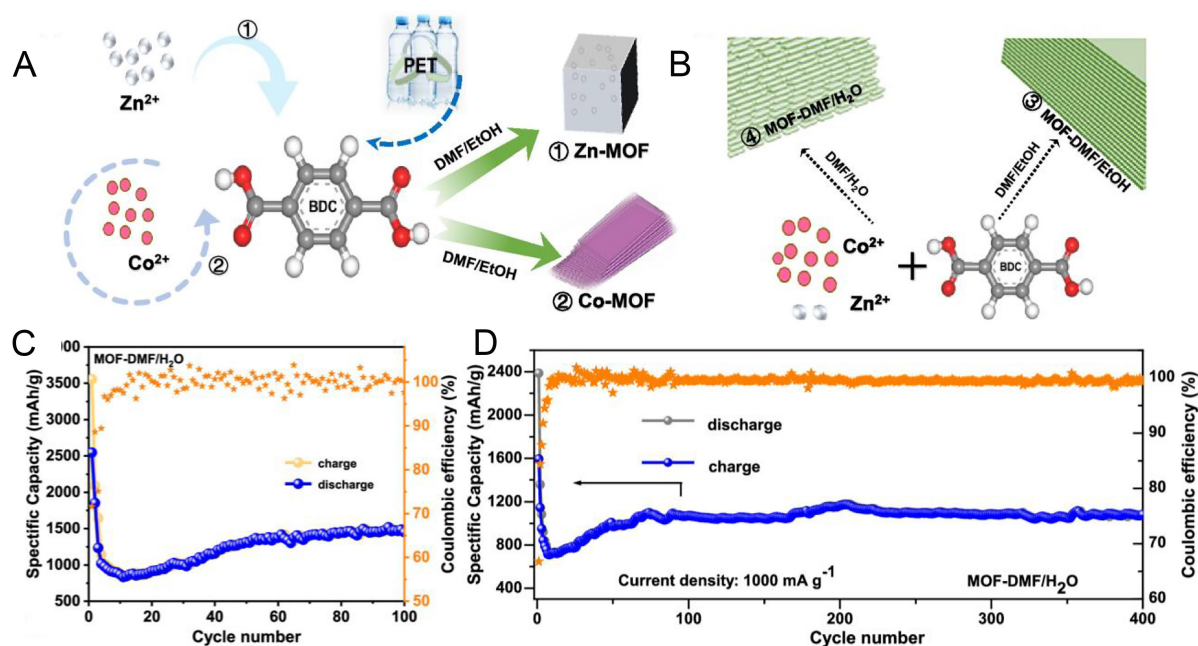


Figure 9. MOF-derived materials for electrochemical energy storage. (A) Schematic preparation processes of Zn-MOF and Co-MOF; (B) Schematic preparation processes of MOF-DMF/EtOH and MOF-DMF/H₂O; (C) Cycling performance and Coulombic efficiency of MOF-DMF/H₂O at a current density of 500 mA·g⁻¹; (D) Long-term cycling performance of MOF-DMF/H₂O at 1000 mA·g⁻¹. All panels are adapted with permission from reference^[102]. Copyright 2024, American Chemical Society. MOF: Metal-organic framework; DMF: *N,N*-dimethylformamide; EtOH: ethanol.

Thermal energy storage

The potential of PET-derived MOFs in thermal energy storage is increasingly recognized, particularly for water adsorption-based heat storage applications. MOFs with high adsorption capacity and thermal stability are especially promising. A comparative study of five MOFs - MIL-101(Cr), UiO-66, MIL-101(Fe), MIL-88B(Fe), and Al fumarate - revealed that MIL-101(Cr) demonstrated superior hydrothermal stability and rapid adsorption kinetics. At a relative pressure (*p/p*₀) of 0.99 and 55 °C, MIL-101(Cr) achieved a water uptake capacity of 1.53 g H₂O g⁻¹, underscoring the importance of high surface area and mesoporosity in enhancing thermal storage performance^[120]. In addition to adsorption-based heat storage, recent work has extended waste PET-derived MOFs toward passive thermal management. Wu *et al.* developed a betaine-assisted one-reactor strategy to convert waste PET and other polyesters directly into functional MOFs. When PET-derived Zn-BDC was incorporated into PVDF films, the resulting composite showed high solar reflectance of 94.4%, mid-infrared emissivity of 95.5%, and an average cooling effect of 9.3 °C below ambient temperature^[260].

Energy conversion

Energy conversion represents an important energy-related application of PET-derived MOFs. PET-derived Cr-MOF and UiO-66 have been investigated for hydrogen storage, with reported H₂ uptake values of 2.1 and 1.2 wt%, respectively^[90,203]. The superior hydrogen-storage behavior of PET-derived Cr-MOF has been attributed to its large surface area, high pore volume, and abundant unsaturated chromium sites. Nevertheless, these systems remain at the laboratory stage, and future studies should evaluate cycling stability, regeneration behavior, moisture tolerance, and scalability under realistic storage conditions. Beyond physical gas storage, PET-derived MOFs also show potential for photocatalytic CO₂ conversion. A PET-based Ni-MOF has been studied as a photocatalyst for CO₂ reduction, achieving a CO production rate of 9.68 × 10³ μmol·h⁻¹·g⁻¹ with 96.7% selectivity for CO over H₂^[89]. This high selectivity favors the formation of value-added carbon-based products while suppressing competitive hydrogen evolution, highlighting the potential of PET-derived MOFs for carbon-neutral energy conversion. In addition, PET-derived MOFs can serve as sacrificial precursors for energy-conversion-related electrochem-

ical materials. For example, waste PET bottles were directly converted into MIL-53(Al), and the resulting MOF was further carbonized into accordion-like hierarchical porous carbon for Zn-ion capacitors, delivering a high capacitance of $335 \text{ F} \cdot \text{g}^{-1}$ at $0.1 \text{ A} \cdot \text{g}^{-1}$, an energy density of $150.3 \text{ Wh} \cdot \text{kg}^{-1}$, and 92.2% capacitance retention after 10,000 cycles^[155]. This result suggests that PET-derived MOFs are not limited to direct gas-storage or photocatalytic functions, but can also act as intermediate platforms for constructing carbon-based energy devices.

Porous MOFs derived from PET demonstrate remarkable potential for energy storage and conversion applications, including supercapacitors, LIBs, thermal energy storage, and photocatalysis [Table 3]. Their hierarchical porosity, tailorable electronic characteristics, and structural robustness contribute to enhanced energy density, power density, and long-term cycling performance. Ongoing developments in MOF design, metal doping, and structural engineering are poised to further unlock the potential of PET-derived MOFs for next-generation sustainable energy technologies.

Catalysis

The exceptional physicochemical properties of PET-derived MOFs have stimulated increasing interest in their use as heterogeneous catalysts or catalyst precursors. Compared with conventional catalysts, PET-derived MOFs combine recycled terephthalate-based linkers with accessible metal nodes, high surface areas, tunable porosity, and confined microenvironments, enabling diverse catalytic transformations. Current studies can be broadly divided into environmental pollutant degradation, CO_2 fixation, nitroaromatic reduction, oxidative desulfurization (ODS), hydrogen generation from liquid hydrogen carriers, and emerging MOF-catalyzed plastic-waste upgrading reactions.

Environmental Catalysis for Pollutant Degradation

Advanced oxidation and catalytic treatment technologies, including photo-Fenton reactions, photocatalysis, electro-Fenton processes, and peroxymonosulfate (PMS)/peroxydisulfate (PDS) activation, have emerged as efficient strategies for degrading persistent organic pollutants in water^[262–264]. MOFs have emerged as a focus of substantial interest because their high specific surface area and tun-

able porosity enable enhanced catalytic performance. Fe-MOFs have shown significant promise as Fenton catalysts due to their inherent water stability, environmental friendliness, and numerous exposed iron active sites^[265]. Additionally, their excellent light absorption enables them to act as photocatalytic semiconductors under irradiation, making them ideal for incorporation into photo-Fenton systems^[266,267]. MOFs offer potential in reducing the negative impacts of algaecides, which are commonly used to manage harmful algal blooms (HABs) in freshwater systems but are often detrimental to water quality^[268,269]. Integrating copper with MOFs represents a novel approach to water remediation. The Cu-based MOFs act as indirect sources of reactive oxygen species (ROS), effectively inhibiting cyanobacterial growth, inducing colony aggregation, and disrupting photosynthetic systems, while exhibiting negligible toxicity toward aquatic organisms such as *Daphnia magna*^[95].

PET-derived Fe-MOFs have been extensively explored for environmental catalysis. For example, a PET-derived Fe-MOF@ Fe_2O_3 composite exhibited exceptional catalytic performance, achieving 99.3% degradation of $15 \text{ mg} \cdot \text{L}^{-1}$ malachite green (MG) within 30 min under visible light irradiation, with a remarkably short residence time of only 20 min^[165]. Similarly, PET-derived MIL-53(Fe), synthesized by Sun *et al.*^[181], demonstrated remarkable photocatalytic efficiency in a photo-Fenton system, achieving 99% degradation of the disinfection byproduct 2,6-dichloro-1,4-benzoquinone (2,6-DCBQ) in 30 min. It also effectively degraded phenol (98%) and bisphenol A (BPA) (> 95%) within 60 min. More recently, Zhang *et al.* reported a room-temperature waste-to-MOF strategy using PET-derived TPA and Fe(III) recovered from spent acid pickling baths to synthesize MIL-88B(Fe). The resulting framework activated PMS and removed 87% of TC hydrochloride within 15 min, while maintaining 96% activity after five cycles^[247].

MOFs have been extensively utilized in the catalytic degradation of dyes and organic contaminants in aqueous environments, beyond their application in photo-Fenton reactions. For instance, MIL-101(Ag) has demonstrated exceptional catalytic capabilities in the reduction of MB, 4-nitrophenol (4-NP), and 4-nitroaniline (4-NA) in the presence of NaBH_4 ,

Table 3. PET-derived MOF-based materials for energy storage and conversion

Types of Energy Storage	Properties	Two-step method			MOFs	Year	Ref.
		Hydrolysis method of waste PET	Synthesis method of PET-derived MOFs	Synthesis conditions			
Chemical energy source	H ₂ uptake = 1.2 wt%	Glycolysis	Solvothermal	120 °C, 4 h	UiO-66(Zr)	2016	[203]
Electric energy		Glycolysis	Solvothermal	100 °C, 24 h	Ni-MOF	2020	[104]
Electric energy	C = 890 F·g ⁻¹ @ 5 mV·s ⁻¹ , C = 913 F·g ⁻¹ @ 1 A·g ⁻¹	Alkaline hydrolysis	Solvothermal	100 °C, 24 h	Ni/Co-MOF	2020	[261]
Electric energy	GCD retention ≈ 98% (400 cycles)	Glycolysis	Solvothermal	100 °C, 24 h	MOF-5	2021	[117]
Electric energy	Coulombic efficiency = 99% (200 cycles)	Glycolysis	Solvothermal	150 °C, 24 h	Co/Ni-MOF	2022	[103]
Electric energy		Alkaline hydrolysis	Solvothermal	120 °C, 20 h	Co/Zn-MOF	2024	[102]
Electric energy	C = 104.8 F·g ⁻¹ @ 0.5 A·g ⁻¹	Alkaline hydrolysis	Solvothermal	180 °C, 24 h	Cu, Zr, Ti-MOF	2023	[133]
Electric energy	Coulombic efficiency = 92% (5,000 cycles)	Glycolysis	Solvothermal	140 °C, 6 h	Zr-MOF	2024	[94]
Chemical energy source		Glycolysis	Grinding + baking	130 °C, 12 h	Ca-MOF, Ba-MOF, UiO-66(Zr)	2024	[107]
Electric energy	C = 353 F·g ⁻¹ @ 0.5 A·g ⁻¹	Glycolysis	Hydrothermal	99 °C, 24 h	Zn-MOF	2024	[157]
Chemical energy Source	H ₂ O uptake ₍₁₎ = 1.15 g _{H2O} /g _{adsr} , H ₂ O uptake ₍₂₎ = 1.53 g _{H2O} /g _{adsr} , H ₂ O uptake ₍₃₎ = 0.78 g _{H2O} /g _{adsr} , H ₂ O uptake ₍₄₎ = 0.77 g _{H2O} /g _{ads}	Glycolysis	Solvothermal	120 °C, 4 h; 210 °C, 8 h; 110 °C, 20 h	UiO-66(Zr) ₁ , MIL-101(Cr) ₂ , MIL-101(Fe) ₃ , MIL-88B(Fe) ₄	2023	[120]
Types of energy storage	Properties	One-pot synthesis		Synthesis conditions	MOFs	Year	Ref.
		Synthesis method of PET-derived MOFs					
Chemical energy source	H ₂ uptake = 2.1 wt%	Hydrothermal		210 °C, 8 h	Cr-MOF	2016	[90]
Electric energy	C = 335F·g ⁻¹ @0.1 A·g ⁻¹ , 10,000 cycles (92.2%)	Solvothermal		180 °C, 12 h	MIL-53(Al)	2023	[155]
Thermal management	Solar reflectance (≈ 94.4%); Mid-infrared emissivity (≈ 95.5%)	Reactor		200 °C, 2 h	Zn, Ni, Co, Ca-MOF	2026	[260]

C: Specific capacitance; GCD: galvanostatic charge-discharge; MOFs: metal-organic frameworks; PET: polyethylene terephthalate.

achieving degradation efficiencies exceeding 93% within 5–10 min^[270] [Figure 10]. In addition, Waribam *et al.* developed a solvent-free rapid synthesis of magnetic MOFs from waste-derived precursors. The resulting Mag-MOF completely degraded an azo dye through a Fenton-like pathway within 30 min and retained 84% activity after five cycles, highlighting the value of solvent-free synthesis and magnetic recoverability for practical environmental cleanup^[248]. Bimetallic MOFs frequently demonstrate enhanced catalytic activity compared to their monometallic counterparts, owing to synergistic

effects between the distinct metal centers^[271]. For example, a Ni/Cu-MOF derived from PET displayed 99% MB degradation under sunlight within 4 h^[272]. Similarly, a Cr-MOF achieved a 92.4% photocatalytic degradation efficiency for TC^[273]. Additionally, MOFs have proven effective in electro-Fenton systems, illustrated by MIL-53(Fe)@Fe₃O₄@C, which reached a degradation efficiency of 91.68% ± 3.61% for salicylic acid (SA)^[131], thereby expanding the potential of MOFs in advanced water treatment strategies. A further example is the construction of a MOF-based photocatalyst from PET waste bottles

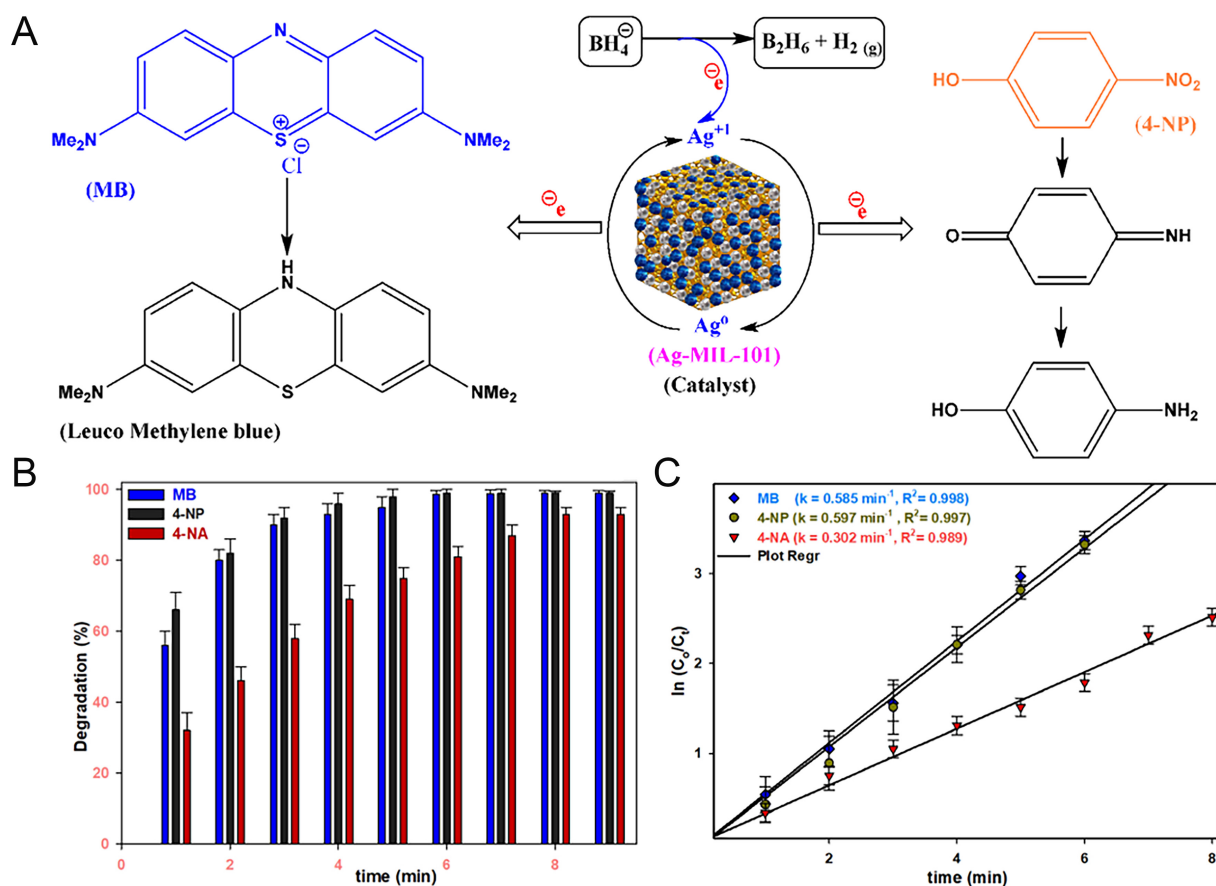


Figure 10. PET-derived MOF-based catalysts for organic pollutant degradation. (A) Proposed mechanism for the reduction of MB and 4-NP in the presence of Ag-MIL-101; (B and C) Kinetic studies of the degradation reactions of common organic pollutants, including MB, 4-NP, and 4-NA. All panels are adapted from reference^[270] under the terms of the Creative Commons Attribution 4.0 International license. Copyright 2024, The Author(s). MOF: Metal-organic framework; PET: polyethylene terephthalate; MB: methylene blue; 4-NP: 4-nitrophenol; 4-NA: 4-nitroaniline.

and spent zinc-carbon batteries for the photodegradation of organophosphorus pesticides, demonstrating that dual-waste-derived MOF catalysts can simultaneously address plastic waste valorization, battery-waste reuse, and pesticide detoxification^[274].

CO₂ fixation and nitroaromatic reduction

The exceptional physicochemical properties of MOFs derived from post-consumer PET have stimulated increasing interest in their use as heterogeneous catalysts or catalyst precursors for value-added chemical conversion. In addition to environmental remediation, PET-derived MOFs have been explored for CO₂ fixation, nitroaromatic reduction, ODS, and hydrogen generation from liquid hydrogen carriers. Their high specific surface area, hierarchical porosity, accessible metal nodes, and tunable linker environments provide abundant active sites and confined microenvironments for heterogeneous

catalytic reactions.

In 2016, Lo *et al.* conducted a seminal study on PET-derived MOF catalysis, demonstrating the catalytic capability of PET-based MIL-47 and MIL-101(Cr) in CO₂ fixation^[149]. The system efficiently converted CO₂ and epoxides into cyclic carbonates under mild conditions, emphasizing its potential for carbon capture and utilization (CCU). This research highlights the viability of PET-derived MOFs as heterogeneous catalysts and supports sustainable CO₂ valorization strategies, providing an energy-efficient method for producing high-value chemicals. Beyond CO₂ fixation, PET-derived MOFs show strong catalytic performance in reduction reactions. Notably, Cu-MOF serves as an eco-friendly catalyst for converting 4-NP to 4-aminophenol (4-AP), a crucial intermediate in pharmaceuticals and dyes, and the amine-functionalized Cu-MOF exhibited an impres-

sive catalytic normalized kinetic rate of $11.28 \text{ mol} \cdot \text{min}^{-1} \cdot \text{mg}^{-1}$, achieving full reduction within 5 min under ambient conditions^[99]. This enhanced performance results from the synergistic interaction between the MOF structure and surface amination, which improves electron transfer and access to active sites.

PET-derived MOFs have exhibited promising potential in ODS and denitrification processes, which are crucial for the deep purification of fossil fuels and the mitigation of environmental pollutants. For instance, an Al-MOF was effectively employed to remove thiophene-based sulfur compounds from both simulated and actual crude oil samples. By optimizing key catalytic parameters, such as temperature, reaction time, and catalyst loading, the desulfurization efficiency reached 90% in real oil samples^[125]. This finding highlights the potential of PET-derived MOFs as next-generation catalysts for industrial-scale fuel purification, offering an eco-friendly alternative to conventional desulfurization methods.

ODS and hydrogen generation

PET-derived MOFs are gaining attention as catalysts for sustainable hydrogen production. A prominent example is the UiO-66-derived $\text{Co@Cr(OH)}_3/\text{ZrO}_2$ hybrid catalyst, created through PET carbonization, which demonstrated outstanding catalytic efficiency in formic acid dehydrogenation. At room temperature, it achieved a turnover frequency (TOF) of $7,685 \text{ h}^{-1}$, releasing 120 mL of hydrogen in just 1.5 min^[127]. The efficiency and stability of this catalyst highlight the promise of PET-derived MOFs in hydrogen storage and production, which are crucial for the clean energy transition.

Emerging MOF-catalyzed plastic-waste upgrading

Recent studies further suggest that MOF catalysis is expanding from PET-derived MOFs toward broader plastic and polyester catalytic upgrading. Qin *et al.* reported a MOF-based photocatalytic strategy for polyester plastic valorization by regulating active sites, demonstrating that MOFs can also serve as catalytic platforms for polyester waste conversion^[275]. In another related study, Das *et al.* reported the selective electrocatalytic production of formic acid from plastic waste using a nickel MOF constructed from a biomass-derived ligand^[276]. Although these two examples are not PET-derived MOFs in the strict

sense, they reveal an emerging complementary direction: MOFs can either be synthesized from PET-derived linkers as value-added products or be used as catalysts for plastic-waste upgrading. A significant advantage of PET-derived MOFs in industrial catalysis is their inherent thermal and chemical stability, ensuring sustained catalytic performance. Unlike traditional catalysts prone to deactivation from sintering or leaching, MOF-based catalysts retain structural integrity through multiple catalytic cycles. Future research should aim to refine MOF architectures via ligand functionalization, metal doping, and hybridization with conductive supports to further boost their catalytic efficiency and selectivity.

PET-derived MOFs show significant promise in industrial catalysis, providing sustainable and scalable solutions for CO_2 fixation, hydrogenation, desulfurization, and hydrogen production. Their modular tunability and exceptional catalytic properties position them as next-generation green catalysts that tackle urgent energy and environmental sustainability challenges. Advancements in structural engineering, composite fabrication, and mechanistic insights will be crucial for transitioning these materials from laboratory research to large-scale industrial use. MOFs demonstrate outstanding cyclic and thermal stability during catalysis, ensuring their long-term viability in industrial applications. Future advancements in material design and synthesis are anticipated to expand their use in chemistry and industrial catalysis [Table 4], offering innovative solutions for green chemistry and sustainable development.

Sensing and detection

The remarkable porosity, high surface area, and adjustable functionality of PET-derived MOF materials render them highly promising for environmental monitoring. These materials have been effectively used for real-time detection of toxic gases, heavy metals, and organic pollutants, aiding pollution prevention and control [Table 5].

PET-derived MIL-53 is acclaimed as a potent adsorbent and stationary phase for liquid chromatography, attributed to its precise pores, extensive surface area, and robust adsorption affinity^[279,280]. Using a green synthesis method, PET waste bottles were hydrolyzed to produce BDC, which served as a

precursor for MIL-53(Al) synthesis. The use of this material in SPME has enabled the efficient extraction of propranolol, a widely screened β -blocker in biological matrices^[126]. The high selectivity and extraction efficiency are attributed to the π - π interactions between the naphthyl moiety of propranolol and the phenyl group of MIL-53(Al)^[281]. PET-derived MIL-53(Cr) exhibits exceptional performance as an HPLC stationary phase, achieving shorter retention times for methylxanthine separation in tea samples compared to traditional C18 columns, while maintaining comparable resolution^[159]. This highlights the promise of PET-derived MOFs in chromatography, presenting sustainable and efficient alternatives to conventional materials.

Lanthanide-based MOFs (Ln-MOFs) have garnered significant attention for their utility in fluorescence sensing applications. This is attributable to their unique “antenna effect”, which enhances the f-f electronic transitions of the incorporated lanthanide ions. This phenomenon results in intense luminescence with high color purity and extended lifetimes^[282-293]. A representative example is the water-stable La-based IISERP-MOF25 reported by Maity *et al.*^[290], which enabled aqueous-phase differentiation and speciation of Fe^{3+} and Fe^{2+} [Figure 11A-F]. The framework exhibited strong blue emission in water, while Fe^{3+} caused rapid and nearly complete fluorescence quenching in less than 1 min, whereas Fe^{2+} produced only negligible quenching. The sensing response remained highly selective in the presence of competing metal ions, and the Fe^{3+} -dependent quenching showed a linear Stern-Volmer relationship with a quenching constant of $1.52 \times 10^4 \text{ L}\cdot\text{mol}^{-1}$ and a detection limit of 3.6 ppm, illustrating the proposed static quenching and regeneration mechanism: Fe^{3+} is accommodated within the N-rich MOF channels to form a nonfluorescent ground-state complex, while subsequent treatment with ascorbic acid reduces Fe^{3+} to Fe^{2+} , allowing Fe^{2+} to leach out and restoring the fluorescence [Figure 11G-I]. The fluorescence intensity was retained over multiple recovery cycles, and powder X-ray diffraction (PXRD) patterns confirmed that the framework crystallinity remained intact after regeneration^[290]. Tb-MOF, with its octacoordinated Tb(III) center, enables the highly sensitive detection of explosives like picric acid (PA) and 2,4,6-trinitrophenol (TNP) through fluorescence quenching^[88]. Likewise, Eu-MOF, synthesized from PET-derived BDC, has been

effectively used for acetone detection, leveraging the d-f transitions of Eu^{3+} and its specific interactions with guest molecules^[250]. La-MOF exhibits luminescence induced by charge transfer from the BDC ligand to La^{3+} . Binding of Fe^{3+} quenches this fluorescence due to strong complexation between Fe^{3+} and the ligand, enabling a detection limit of $0.147 \mu\text{mol}\cdot\text{L}^{-1}$ - a level of sensitivity and selectivity exceeding that of most conventional Fe^{3+} sensors [Figure 11J-L]^[146].

Cu-based MOFs exhibit superior sensing abilities for VOCs due to their intrinsic porosity and strong adsorption affinity. Kaur *et al.* leveraged a PET-derived Cu-MOF to detect acetone, achieving a detection limit of 20 ppm via an absorption quenching mechanism^[97]. Beyond acetone, Cu-MOFs have also been utilized to detect ethanol and methanol, employing fluorescence and electrochemical methods to assess their sensing performance^[294].

Integrating PET-derived MOFs with functional materials can enhance sensing performance. For instance, a MIL-101(Cr) and PANI composite was developed for Pb^{2+} detection. The π - π stacking between PANI chains and MIL-101(Cr) benzene rings, along with Lewis acid-base interactions, enabled rapid electron transduction, markedly improving sensitivity and selectivity^[295]. The present study reports the development of a high-performance flexible sensor derived from waste PET through a two-step process. First, a Ni-MOF was synthesized using the PET waste as a carbon source. The Ni-MOF was then subjected to laser-induced carbonization, resulting in the formation of a graphene/nickel carbide hybrid material. This hybrid exhibited exceptional electrical conductivity, with a sheet resistance of $6.2 \pm 3.4 \Omega$. The flexibility and high responsiveness of the sensor to mechanical bending make it a promising candidate for applications in wearable electronics and medical monitoring systems^[185].

The structural versatility of PET-derived MOFs has enabled a diverse array of sensing applications, from chromatographic analysis to fluorescence and electrochemical detection. This adaptability allows precise tuning of adsorption affinity, electronic properties, and fluorescence mechanisms, making MOFs well suited for monitoring a wide range of environmental pollutants. Ongoing developments in MOF

Table 4. PET-derived MOFs for catalysis and chemical conversion

Application and properties	Two-step method			MOFs	Year	Ref.
	Hydrolysis method of waste PET	Synthesis method of PET-derived MOFs	Synthesis conditions			
Methyl Orange: Removal rate = 85% (5 min)	Alkaline hydrolysis	Solvothermal	Room temperature, 48 h	Cu-MOF	2018	[277]
CO ₂ → CO (9.68 × 10 ³ μmol·h ⁻¹ ·g ⁻¹), Sel(H ₂) = 96.7%	Alkaline hydrolysis	Solvothermal		Ni-MOF	2021	[89]
Organic pollutant dyes: Degradation = 95% (12 min)	Glycolysis	Solvothermal	110 °C, 36 h	Cu-Zn-MOF	2023	[105]
Salicylic acid: Removal rate = 49.35% ± 3.55% (180 min)	Alkaline hydrolysis	Solvothermal	100 °C, 12 h	MIL-53(Fe)	2023	[131]
Methylene blue: Degradation = 99% (1,200 mg·L ⁻¹)	Glycolysis	Hydrothermal	150 °C, 12 h	Ni/Cu-MOF	2024	[272]
Environmental Catalysis	Alkaline hydrolysis	Hydrothermal	120 °C, 24 h	UiO-66	2024	[127]
Pollutant dyes: Degradation = 93% (8 min)	Glycolysis	Hydrothermal	220 ± 5 °C, 8 h	MIL-101(Ag)	2024	[270]
Application and properties	One-pot synthesis				Year	Ref.
	Synthesis method of PET-derived MOFs	Synthesis conditions	MOFs			
Propylene carbonate: Conversion = 95%; Cyclohexene oxide: Conversion > 90%	Hydrothermal	200 °C, 96 h; 160 °C, 72 h; 160 °C, 72 h; 210 °C, 5 h; 220 °C, 8 h	MIL-47, MIL-53(Cr), MIL-53(Al), MIL-53(Ga), MIL-101(Cr)		2016	[149]
Toluene: Q = 42 mmol·g ⁻¹	Solvothermal	215 °C, 8 h	MIL-101(Cr)		2022	[161]
Malachite green (15mg·L ⁻¹) Degradation = 99.3% (30 min)	DBD Plasma method		Fe-MOF		2023	[165]
Steam generation 2.46 kg•(m ² ·h) ⁻¹ , Tetracycline: Removal rate = 83.4%	Solvothermal	210 °C, 8 h	Cr-MOF		2023	[273]
S: Removal rate = 90%	Hydrothermal	215 °C , 8 h	MIL-53(Al)		2023	[125]
Toluene: Q = 15.2 mmol·g ⁻¹	Hydrothermal	215 °C, 8 h	MIL-101(Cr)		2024	[215]
Application and properties	Mechanochemistry milling				Year	Ref.
	Hydrolysis method of waste PET	Synthesis method of PET-derived MOFs	Synthesis conditions	MOFs		
4-NP → 4-AP Catalytic reduction rate = 11.28 mol•min ⁻¹ ·mg	Alkaline hydrolysis	Ball milling	110 °C, 72 h	Cu-MOF	2023	[99]
Application and properties	In situ growth				Year	Ref.
	Support	Synthesis method of PET-derived MOFs		MOFs		
As: Q = 173.3 mg·g ⁻¹	Carbon Nanotubes	Solvothermal		Ni-MOF	2022	[278]
CV: Removal = 58.80% (24 h). MG, AG, MO Removal = 64.82%, 61.61%, 21.12%	PET	Hydrothermal		UiO-66	2023	[180]
2,6-DCBQ, phenol, BPA: Degradation = 99% (30 min), 98% (60 min), 95% (60 min)	PET	Solvothermal		MIL-53(Fe)	2023	[181]
Benzene: Q _{max} = 68.72 mg·g ⁻¹ , Toluene: Q _{max} = 91.63 mg·g ⁻¹ , m-Xylene: Q _{max} = 78.47 mg·g ⁻¹	PET	Solvothermal		MIL-101(Fe)	2024	[182]
DMNP: Degradation t _{1/2} = 43.3 min	PET	Solvothermal		UiO-66	2024	[108]

Sel: Selectivity; CO₂ → CO: reaction kinetic rate; DBD: dielectric barrier discharge; 4-NP: 4-nitrophenol; 4-AP: 4-aminophenol; CV: Crystal violet; MG: malachite green; AG: alizarin green; MO: methyl orange; 2,6-DCBQ: 2,6-dichloro-1,4-benzoquinone; BPA: bisphenol A; DMNP: dimethyl 4-nitrophenyl phosphate; MOFs: metal-organic frameworks; PET: polyethylene terephthalate.

functionalization, composite engineering, and

Table 5. PET-derived MOFs for sensing and environmental monitoring

Application	Properties	Two-step method			MOFs	Year	Ref.
		Hydrolysis method of waste PET	Synthesis method of PET-derived MOFs	Synthesis conditions			
Chemical substance detection		Alkaline hydrolysis	Hydrothermal	Room temperature	La-MOF	2019	[88]
Acetone	LOD ~20 ppm	Alkaline hydrolysis	Solvothermal	85 °C, 24 h	Cu-MOF	2020	[97]
Propranolol	LOD = 1.7 µg·L ⁻¹	Alkaline hydrolysis	Solvothermal	220 °C, 72 h	MIL-53(Al)	2020	[126]
Application	Properties	One-pot synthesis			MOFs	Year	Ref.
		Synthesis method of PET-derived MOFs		Synthesis conditions			
Chromatographic detection		Hydrothermal		210 °C, 72 h	MIL-53(Cr)	2021	[159]
Application	Properties	Mechanochemistry Milling			MOFs	Year	Ref.
		Hydrolysis method of waste PET	Synthesis method of PET-derived MOFs	Synthesis conditions			
Fe ³⁺	Quenching constant = 5.29×10^3 (mol·L ⁻¹) ⁻¹ ; LOD = 0.147 µmol·L ⁻¹	Ball milling Alkaline hydrolysis	ball milling	600 r·min ⁻¹ 4 h	La-MOF	2024	[146]
Application	Properties	In situ growth			MOFs	Year	Ref.
		Support		Synthesis method of PET-derived MOFs			
Smart Sensing	Sheet resistance = $6.2 \pm 3.4 \Omega$	PET		Solvothermal	Ni-MOF	2024	[185]

LOD: Detection limit; MOFs: metal-organic frameworks; PET: polyethylene terephthalate.

integration with electronic platforms will be crucial in accelerating the translation of these materials from laboratory research to practical environmental monitoring solutions.

Critical comparison with conventional MOFs

Performance comparisons between PET-derived and conventional MOFs are meaningful only when the framework identity, activation protocol, particle form, temperature, pressure or concentration, solution chemistry, contact time, and calculation basis are comparable. Recent syntheses and reviews show that PET-derived materials can approach conventional analogs in crystallinity, surface area, adsorption, catalysis, and electrochemical behavior, but apparent advantages can disappear when measurements use different conditions^[296,297]. Accordingly, the values in Tables 2–5 should be read as a map of reported performance rather than a universal ranking.

For adsorption and water-treatment applications, uptake capacity should be compared at the same equilibrium concentration, pH, ionic strength,

temperature, and adsorbent dose; kinetics and regenerability should be reported alongside maximum capacity. A recent waste-derived MIL-101(Cr) study illustrates how precursor route, post-synthetic functionalization, and test conditions jointly determine PFAS removal, making comparison with commercial-precursor MIL-101(Cr) more informative than comparison with unrelated frameworks^[298]. Similar constraints apply to gas adsorption, where pressure, temperature, humidity, pelletization, and usable working capacity matter, and to catalysis and energy storage, where conversion, selectivity, loading, current density, electrolyte, and cycling protocol must be matched.

INDUSTRIALIZATION AND COMMERCIALIZATION

Commercial MOF manufacture demonstrates that scale-up is technically possible, but it does not establish that PET-derived MOFs are commercially ready. Industrial studies emphasize space-time yield, safe and inexpensive reagents, solvent recovery, robust washing and activation, shaping, and reproducible

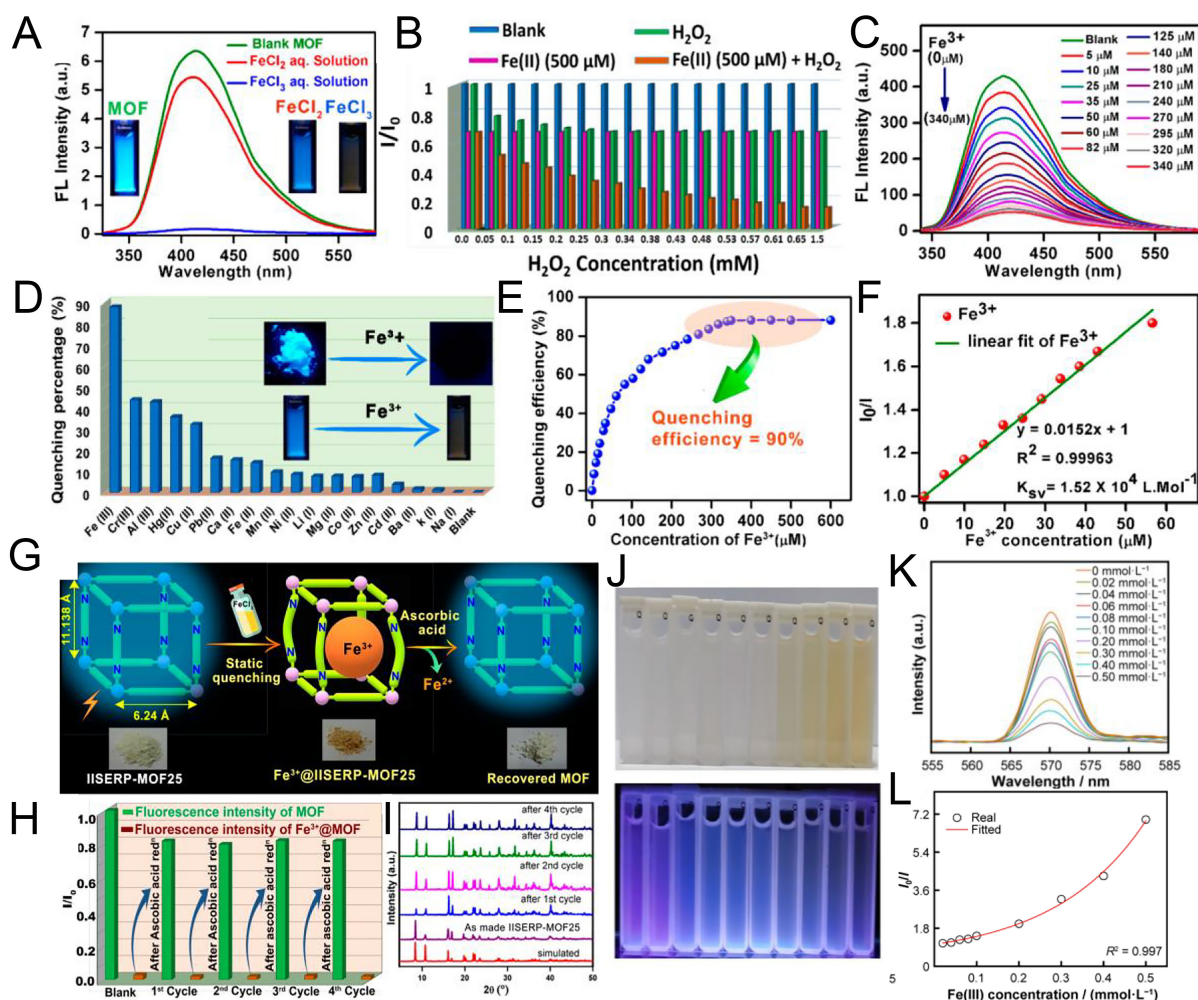


Figure 11. PET-derived MOF-based fluorescent sensors for Fe^{3+} detection. (A) Solution-state fluorescence spectra of IISERP-MOF25 in the absence and presence of Fe^{2+} or Fe^{3+} ; (B) Relative fluorescence intensity of IISERP-MOF25 after the addition of different amounts of peroxide, Fe^{2+} , or both Fe^{2+} and peroxide, leading to the *in situ* generation of Fe^{3+} ; (C) Fluorescence quenching efficiency in FeCl_3 solutions with different concentrations; (D) Solid-state and solution-state fluorescence quenching of IISERP-MOF25 by Fe^{3+} ions in the presence of different metal ions, including Fe^{2+} ; excitation was performed at 300 nm, and emission was monitored at 413 nm; (E) Quenching efficiency toward Fe^{3+} ions; (F) Color change of activated IISERP-MOF25 from colorless to brown after soaking in 0.33 mM FeCl_3 solution, together with the Stern-Volmer plot at low Fe^{3+} concentrations; (G) Proposed mechanism of static fluorescence quenching of IISERP-MOF25 through ground-state nonfluorescent complex formation with Lewis-acidic Fe^{3+} ions. The MOF has pore-window dimensions of $11.138 \text{ \AA} \times 6.24 \text{ \AA}$, allowing the accommodation of Fe^{3+} , whereas weaker interaction with Fe^{2+} is attributed to its larger size and possible leaching; (H) Representative diagrams for fluorescence recovery studies and fluorescence intensities after four recycling runs; (I) PXRD patterns of the MOF after each ascorbic acid reduction step; (J) Photographs of La-MOF suspensions in the presence of Fe^{3+} at concentrations of 0, 0.02, 0.04, 0.06, 0.08, 0.10, 0.20, 0.30, 0.40, and 0.50 $\text{mmol} \cdot \text{L}^{-1}$ under natural light and UV light; (K) Fluorescence spectra of La-MOF solution with various Fe^{3+} concentrations; (L) Plots of relative fluorescence intensity of La-MOF solution with various Fe^{3+} concentrations. (A–I) are adapted with permission from reference^[290]. Copyright 2019, American Chemical Society. (J–L) are adapted with permission from reference^[146]. Copyright 2024, The Author(s). MOF: Metal-organic framework; PET: polyethylene terephthalate; PXRD: powder X-ray diffraction.

quality as decisive variables^[299,300]. Continuous synthesis in water or ethanol and scalable low-waste routes show how conventional MOF production can move beyond small solvothermal batches^[301–303]. BASF has also publicly reported industrial-scale MOF production for carbon-capture applications, providing relevant commercial context while not constituting

direct evidence for PET-derived products^[304].

For PET-derived MOFs, the central industrial challenge is the interaction between variable waste feedstock and demanding product specifications. Colorants, multilayer components, fillers, labels, residual food, and polymer blends can change depolymeriza-

tion, linker purity, nucleation, porosity, and batch reproducibility. A viable process therefore requires feedstock specifications, rapid incoming-quality tests, impurity-tolerant chemistry or selective purification, and release criteria linking linker composition to MOF performance. Metal-source purity, solvent and metal recovery, mother-liquor reuse, corrosion, wastewater treatment, and worker exposure must be designed into the flowsheet rather than treated as downstream corrections.

Product shaping is equally important. Industrial adsorbents and catalysts are used as pellets, granules, coatings, membranes, or structured contactors rather than loose laboratory powders. Binders and shaping conditions can reduce accessible porosity or alter mass transfer, whereas attrition resistance, mechanical strength, heat transfer, pressure drop, regeneration, and long-term cycling determine practical value. PET-derived MOFs should therefore be evaluated through staged technology-readiness milestones: reproducible kilogram-scale synthesis, impurity and recycle-loop tolerance, shaping and device integration, application-relevant durability, pilot operation, and validated quality-control procedures.

TECHNO-ECONOMIC FEASIBILITY

This review did not perform an original techno-economic analysis. The following assessment is qualitative because consistent process inventories, equipment sizing, yields, recycle rates, and market assumptions are not available for PET-to-MOF routes. Published MOF cost studies nevertheless show that synthesis route, solvent use, labor, throughput, yield, and scale strongly affect estimated production cost^[299,305-307]. These findings should be transferred to PET-derived MOFs cautiously because waste handling and linker recovery add operations that are absent from virgin-linker syntheses.

The economic boundary begins with collection, sorting, washing, size reduction, and transport of PET. Although waste PET may have a low or even negative acquisition cost, heterogeneous feedstock increases analytical, rejection, and purification costs. Depolymerization economics depend on reagent stoichiometry, catalyst life, temperature, residence time, corrosion-resistant equipment, conversion, monomer recovery, and the treatment or valoriza-

tion of EG and other coproducts. Linker precipitation, neutralization, washing, drying, and quality control may dominate the advantage of avoiding commercial TPA when high purity is required.

MOF synthesis adds metal salts, modulators, solvent, heating, mixing, separation, washing, activation, solvent recovery, and shaping. Key sensitivities are solids concentration, space-time yield, solvent recycle fraction, metal utilization, isolated yield, batch-cycle time, energy for drying and activation, labor, wastewater treatment, and product specification. Mechanochemical, microwave, aqueous, and one-pot routes may reduce selected burdens, but each transfers costs to equipment, electricity, mixing, heat removal, or process control. A defensible future analysis should report a functional unit, plant capacity, mass and energy balances, capital and operating assumptions, coproduct allocation, product price basis, uncertainty ranges, and sensitivity analysis.

LIFE-CYCLE ASSESSMENT AND ENVIRONMENTAL IMPACTS

No original life-cycle assessment (LCA) was conducted for this review. Claims that PET-derived MOFs are environmentally preferable therefore remain hypotheses unless evaluated using consistent functional units and system boundaries. Existing MOF LCAs demonstrate that synthesis route, solvent, metal precursor, energy source, yield, activation, and application performance can reverse a conclusion based only on recycled feedstock content^[308-310].

A cradle-to-gate assessment should include PET collection and sorting; washing and size reduction; depolymerization reagents, catalysts, heat, and pressure; neutralization and salt generation; linker isolation and purification; metal-salt production; MOF synthesis, washing, solvent recovery, drying, and activation; emissions controls; water consumption; and treatment of liquid and solid residues. A cradle-to-grave or circular assessment should additionally include shaping, transport, use-phase regeneration, performance decay, metal or linker recovery, and end-of-life disposal or recycling. Toxicity and resource-depletion indicators are particularly important where chromium, cobalt, nickel, strong acids or bases, or solvents such as DMF are used.

Avoided burdens may include displacement of virgin TPA, reduced PET disposal, recovery of metals from wastewater, or useful coproducts; however, these benefits require transparent allocation and a credible counterfactual. Conversely, intensive purification can offset the benefit of a waste-derived linker. Dual-waste and catalytic depolymerization routes illustrate the potential for process integration, but comparative environmental claims require measured inventories rather than qualitative labels such as “green” or “low cost”^[298,311]. Future studies should compare PET-derived and conventional MOFs at equal delivered function - for example, kilograms of pollutant removed over a specified number of regeneration cycles - rather than per kilogram of material alone.

CONCLUSION AND OUTLOOK

The conversion of waste PET into MOFs has garnered substantial research attention in recent years. Through chemical recycling and solvothermal synthesis techniques, PET has been effectively transformed into MOF materials exhibiting high specific surface areas, tunable pore sizes, and diverse surface functionalities. These PET-derived MOFs have shown potential in environmental remediation, gas adsorption and separation, catalysis, energy storage and conversion, and sensing applications, demonstrating that waste PET can serve not only as a recyclable polymer resource but also as a precursor for value-added porous materials.

As global plastic pollution intensifies, high-value recycling and conversion of PET waste, such as plastic bottles and packaging, have emerged as crucial areas of focus in green chemistry and materials science. PET waste, abundant in polyester, offers a low-cost source for MOF precursors while mitigating environmental pollution. Consequently, research on PET-derived MOFs holds significant strategic importance for environmental sustainability, resource recycling, and the development of functional materials. Therefore, future work in this field should focus on thoroughly exploring the diversification of raw materials, optimizing synthesis methods, and addressing industrialization challenges to advance the application of PET-derived MOFs in energy storage, catalysis, pollution control, and related areas:

(1) Recycling potential of PET waste

PET waste presents distinct challenges and opportu-

nities for recycling. Unlike PET plastic bottles, PET waste often includes various dyes, additives, and impurities, complicating their use in MOF synthesis. By designing a rational synthesis process, the porous network structure of PET-based materials can be utilized to construct the hierarchical channels of MOFs, enhancing their specific surface area and mass-transfer efficiency. This improvement boosts performance in applications like catalysis and gas separation. Consequently, future efforts should focus on the targeted degradation of PET and the regulation of MOF structures to explore their potential in producing high-value materials.

(2) Industrial challenges and future development directions in CO₂ storage and application in coal mining and fire protection Despite the promising laboratory performance of PET-derived MOFs, their practical application still faces challenges in scalable synthesis, cost control, solvent reduction, shaping, mechanical strength, and long-term stability. (i) For CO₂ storage and capture, future studies should focus on humidity resistance, adsorption selectivity, regeneration energy, cycling stability, and compatibility with fixed-bed or membrane-based systems; (ii) In coal-mining applications, PET-derived MOFs may be explored for CO₂/CH₄ separation, methane capture, and toxic-gas monitoring, but their moisture tolerance, dust resistance, and mechanical durability must be improved; (iii) In fire protection, PET-derived MOFs, especially Al-based MOFs, may serve as flame-retardant fillers for polymer composites by promoting char formation and improving barrier effects. Future work should further evaluate their polymer compatibility, smoke suppression, mechanical reinforcement, and large-scale processing feasibility.

Overall, PET-derived MOFs represent an attractive platform for circular materials design by integrating waste PET valorization with high-value functional applications. Continued progress in complex feedstock utilization, industrial CO₂ capture, fire-protective polymer composites, green synthesis, and process scale-up will be critical for translating this field from laboratory research toward practical sustainable technologies.

DECLARATIONS

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The HKUST-1 structure image used in the upper-right corner of the Graphical Abstract was obtained from Wikimedia Commons: Tony Boehle, “HKUST-1 activated.png”, and is used under the Creative Commons Attribution-ShareAlike 3.0 Unported License (CC BY-SA 3.0). The image was incorporated into the Graphical Abstract and adjusted only in size and position. Source: https://commons.wikimedia.org/wiki/File:HKUST-1_activated.png

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Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool ChatGPT by OpenAI (released 2022-11-30) was used for language polishing and for generating several minor illustrative graphical elements in the Graphical Abstract and [Figures 2-5](#), including the plastic bottle elements in the Graphical Abstract. These AI-assisted graphical elements were used only for schematic illustration. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

Chen, X. is an Editorial Board Member of *Greenverse Science*, and Ran, C. is affiliated with

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Ethical approval and consent to participate

Not applicable.

Consent for publication

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