

Ionic liquids in reticular materials: Synthesis strategies, structural modulation, and functional applications

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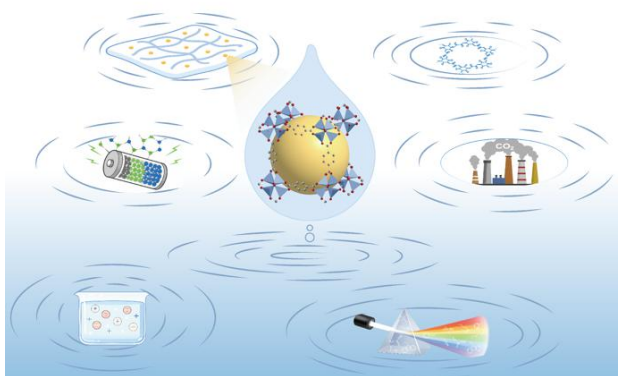
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Ionic liquids provide tunable molecular platforms for constructing functional reticular materials by regulating pores, microenvironments, and frameworks, enabling improved CO₂ capture/conversion, catalysis, separation, and energy applications.

Ionic liquids in reticular materials: Synthesis strategies, structural modulation, and functional applications

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ABSTRACT: Ionic liquids (ILs), as a novel class of molecular platforms with structural tunability, play a significant role in the construction of functional composite materials. Their structural designability enables them to function not only as conventional solvents but also as synthetic media, pore modifiers, functional components, and structure-directing agents. The combination of ILs with reticular materials generates functionalized systems with synergistic effects. The introduction of ILs can modulate the pore architecture, chemical microenvironment, and stacking modes of reticular materials, endowing them with superior performance in catalysis, separation, and energy-related applications that surpass those of single-component materials. This review systematically summarizes the research progress on the application of ILs in reticular materials. First, the synthetic strategies and structure-regulation principles of IL/reticular material composites are analyzed. Second, the multifunctional roles of ILs in the synthesis of reticular materials—as solvents, templates, and structure-directing agents—are summarized. Subsequently, their application progress in CO₂ capture and conversion, catalysis, separation, and energy-related fields is systematically introduced. Finally, the challenges and future directions in this field are discussed. This review aims to provide a systematic theoretical reference for researchers working on porous materials, ionic liquids, and functional composites.

KEYWORDS: ionic liquids, structurally tunable, composite structure, reticular materials

Introduction

Reticular chemistry refers to the chemistry of linking molecular building blocks through strong chemical bonds to form crystalline extended structures¹. Represented by Metal-Organic Frameworks (MOFs) and Covalent Organic Frameworks (COFs), reticular chemistry has experienced rapid development over the past two decades. Reticular materials, characterized by high specific surface areas, well-defined pore architectures, and designable chemical environments, exhibit broad application prospects in gas adsorption, catalysis, separation, and energy storage². Fig1 highlights the remarkable achievements in the MOF field over the past three decades, as evidenced by the unprecedented diversity in both structures and materials. The number of reported MOF structures has exceeded 100,000, with predicted structures surpassing 500,000, and multiple databases such as CSD MOF and CORE MOF continue to systematically catalog this expanding chemical space³. The chemical diversity is equally impressive, with over 65 metal elements and more than 10,000 organic linkers successfully integrated into MOF structures, greatly broadening the possibilities for material design⁴. COFs, on the other hand, are crystalline porous materials composed of light elements (B, C, N, O,

Si) linked by strong covalent bonds, featuring high thermal stability, chemical stability, and high porosity⁵. These characteristics enable their widespread application in separation, photo/electrocatalysis, energy storage, and biomedicine⁶.

In recent years, leveraging the concepts of reticular chemistry, researchers have linked various building blocks to obtain a wide range of extended structures. In these frameworks, the well-established knowledge of organic synthesis and the precise control over inorganic units with diverse geometries and compositions have been effectively combined⁷.

Framework structures such as MOFs and COFs exhibit broad application prospects in gas adsorption and separation, catalysis, energy storage, and sensing. However, practical applications still face several key challenges. First, from a synthetic perspective, traditional methods for reticular materials primarily include solvothermal synthesis, microwave-assisted synthesis, and mechanochemical synthesis. However, these conventional methods have inherent limitations. For instance, traditional solvothermal synthesis requires harsh conditions (high temperature, high pressure, and long reaction times)⁸, limiting its scalability. Moreover,

conventional synthesis often relies on a trial-and-error approach, lacking a clear structural correspondence between reactants and products, making it difficult to achieve precise, targeted synthesis of desired structures⁹. Second, from a structural modulation standpoint, most two-dimensional reticular materials adopt the overlapping AA stacking mode shown in Fig 2a. Due to weak interlayer interactions, these materials typically form polycrystalline powders or nanosheets rather than single crystals with three-dimensional order, making

precise control of stacking modes challenging¹⁰. Finally, regarding performance and applications, COFs suffer from poor film-forming ability and relatively large pore sizes, limiting their application in membrane separation¹¹. Additionally, reticular materials generally face issues of insufficient stability; due to inadequate framework rigidity, some reticular materials are prone to structural collapse and degradation or deactivation under harsh conditions such as strong acids or bases¹².

MOF-WORLD JOURNEY: WHAT HAS BEEN ACHIEVED?

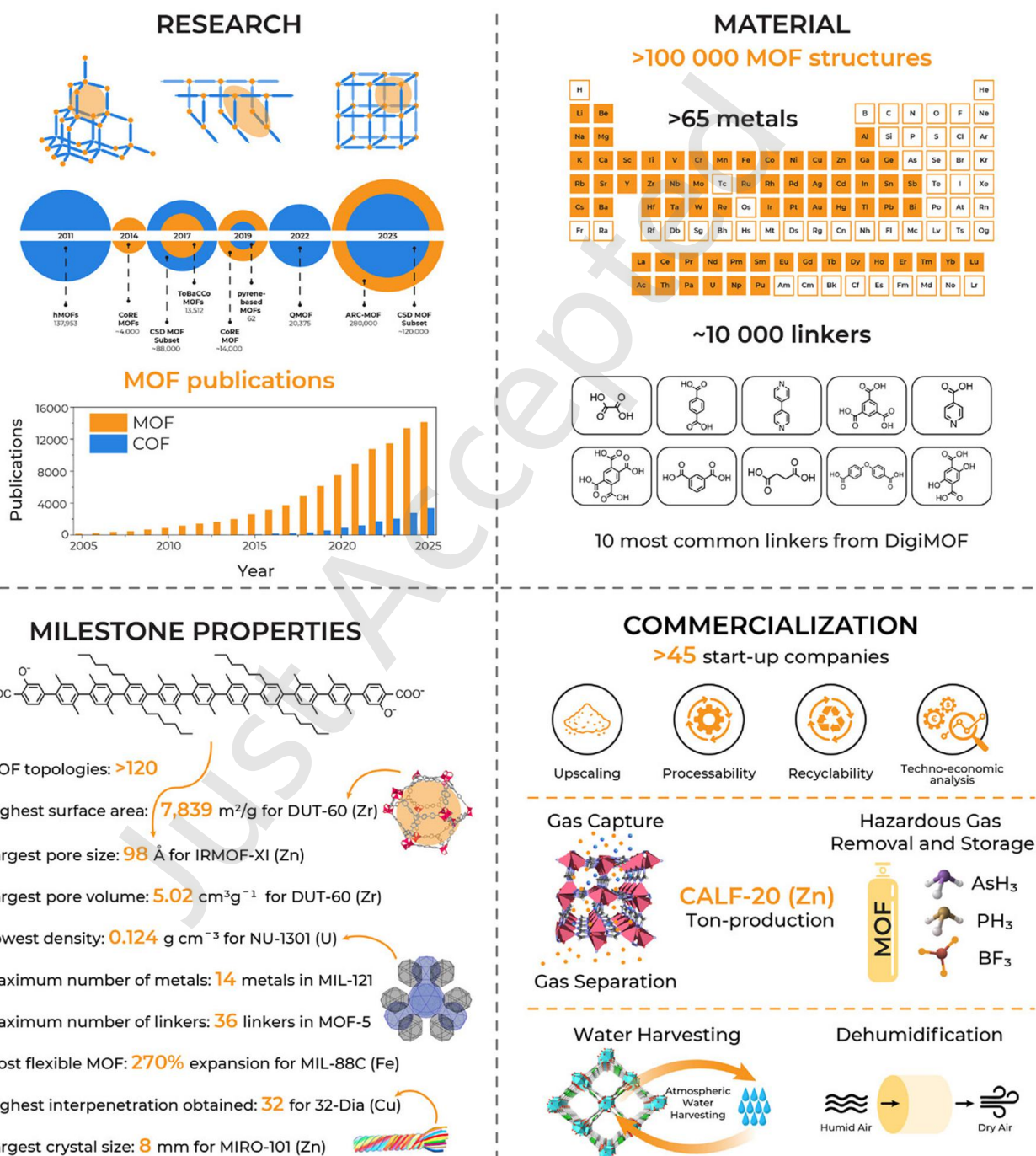


Fig1. The key milestones in how MOFs have developed over the past 30 years. ³ Copyright 2025, The Authors, published by John Wiley and Sons.

In summary, to further enhance the versatility of reticular materials, novel strategies are urgently needed to overcome their deficiencies in synthesis and performance. In this context, ILs—a class of low-melting

salts composed entirely of cations and anions—occupy a significant position in green chemistry due to their negligible vapor pressure, wide liquid range, high thermal stability, and structural designability¹³. They provide a

unique molecular toolbox for constructing novel composite materials. Relevant studies have shown that the role of ILs in reticular material research extends far beyond that of conventional solvents, encompassing multiple functions such as synthetic media, pore modifiers, functional components, and structure-directing agents. For example, Yuan and co-workers systematically reviewed recent progress in solution-processable MOFs via strategies including direct dispersion (Fig 2b), surface modification, controlled calcination, and bottom-up synthesis¹⁴. Fig 2c illustrates the formation process of ZIF- In conclusion, the combination of ILs and reticular 8/IL composite materials. Furthermore, they systematically discussed the interesting applications of solution-processable MOF systems in liquid adsorbents, molecular capture, sensing, and separation. This work provided systematic theoretical guidance for the application of ILs in the synthesis of MOF materials. Meanwhile, He and co-workers developed a "top-down" strategy for preparing solution-processable COFs by introducing intermolecular hydrogen bonding and π - π interactions via ILs¹⁵. As shown in Fig 2d, this method involves heat-treating three COF powders linked by imine, azine, and β -ketoenamine bonds in 1-methyl-3-octylimidazolium bromide ([C₈mim][Br]) ionic liquid, yielding colloidal COF solutions. The treated COFs retained their original chemical structures and crystallinity, with particle sizes reduced to approximately 100 nm, and could be well dispersed in common organic solvents such as ethanol, dichloromethane, acetone, and water, forming stable colloidal solutions and enabling solution processability. The π - π interactions and C-H $\cdots$ π interactions between IL cations and the conjugated structures in COFs played a crucial role in preparing solution-processable COF colloids. This work provides new insights for constructing solution-processable COFs, facilitating their practical applications, and potentially expanding the application scope of COF materials.

In conclusion, the combination of ILs and reticular materials is not a simple composite but rather forms functionalized systems with synergistic effects. This review aims to systematically outline the research progress on the application of ILs in reticular materials. First, the multifunctional roles of ILs in the synthesis of reticular materials—as solvents, templates, and structure-directing agents—are summarized. Second, the synthetic strategies and structure-regulation principles of IL/reticular material composites are analyzed. Third, their application progress in CO₂ capture and conversion, catalysis, separation, and energy storage is systematically introduced. Finally, the challenges and development directions in this field are discussed.

2. Structural Modification and Property Regulation:

Reticular materials, owing to their ordered pore structures formed by linking organic molecules through strong chemical bonds, enable precise pore-size control. The pore structures provide abundant active sites, and the high specific surface area endows these materials with significant application potential in adsorption, catalysis, storage/conversion, sensing, and detection¹⁶.

However, reticular materials suffer from issues such as poor interfacial compatibility, time- and energy-consuming synthesis processes, insufficient application stability, susceptibility to defects, and inadequate electron density in the framework²⁰. Therefore, optimizing synthetic strategies and integrating multifunctional guests—such as conductive media and catalysts—into reticular material hosts is necessary to enhance their performance and broaden their applicability²¹.

This design inevitably introduces challenges in synthesizing and regulating the complex interactions among multiple components. Introducing multifunctional guests becomes an ideal choice for simplifying the system, with ILs standing out due to their flexible multifunctional properties. ILs have diverse applications in the structural design of reticular materials, and their structural design should be considered based on their specific applications. The introduction of ILs provides a novel design approach for diversifying synthesis, functionalizing design, and optimizing the performance of reticular materials.

2.1 Synthetic Strategies for IL/Reticular Material Composites:

Both reticular materials and ILs are considered "designable" materials in a general sense. The pore dimensions and functional groups of reticular materials can be precisely tuned by selecting different building blocks. For instance, Li and co-workers exploited the unique property of dopamine—existing as small molecules under acidic conditions and as polymers under basic conditions—to graft small-molecule dopamine onto one-dimensional pore walls via esterification, reducing the 1D pore size from 1.25 nm to 0.71 nm, thereby achieving directional regulation of both the 1D in-plane pores and the 2D interlayer channels of COF membranes²². Meanwhile, the combinations of IL cations and anions are virtually limitless, endowing them with specific solubility, polarity, acidity/basicity, or catalytic activity²³. The core challenge in combining these two materials lies in efficiently, stably, and uniformly introducing ILs into the nanoconfined spaces of reticular materials. Based on the strength of interactions between ILs and the reticular framework, introduction methods can be categorized into physical and chemical approaches. The following sections describe several methods for introducing ILs into reticular materials.

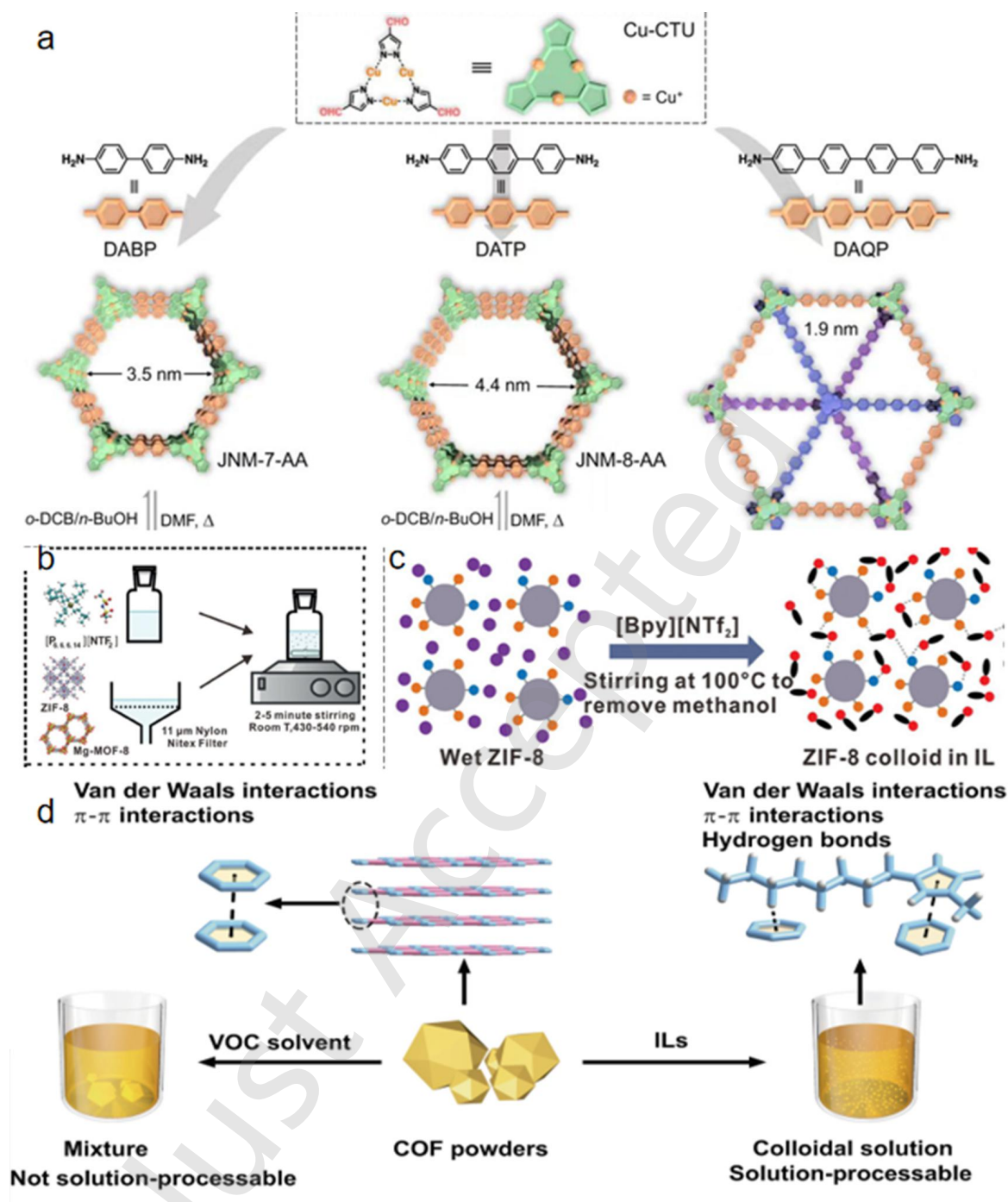


Fig2.(a) Design of JNMs and Solvent-, Acid-, and Heat-Triggered Reversible Structural Transitions.¹⁷ Copyright 2024, The Authors, published by Springer Nature. (b) Direct Dispersion of MOFs in Ionic Liquids.¹⁷ (c) Schematic Diagram of ZIF-8/IL Porous Liquid Formation.¹⁸ Copyright 2024, The Authors, published by John Wiley and Sons.(d) Schematic Diagram of the Solution-Processed COF Preparation Process.¹⁹ Copyright 2023, The Authors, published by Springer Nature

2.1.1 Physical Introduction (Physical Impregnation and Capillary Action):

Introducing ILs into reticular materials via physical means is a common approach. Utilizing the enormous specific surface area and abundant nanopores of reticular materials, liquid ILs are drawn into their pores through physical adsorption (impregnation) or capillary condensation²⁴. In some studies, COF materials are soaked in IL solutions, allowing ILs to enter the pore

structures via physical adsorption or filling. By contacting ILs with COF precursors or pre-synthesized COF materials, interactions such as electrostatic forces and hydrogen bonds facilitate IL entry into the COF pores, thereby modifying COF properties — for example, enhancing gas separation selectivity or catalytic activity. As shown in Fig 3a, Wang and co-workers introduced imidazolium-based ILs into COF membranes via physical impregnation to overcome the limitations of COF materials (poor film-forming ability and relatively large

pore sizes) for gas separation membranes. The IL-modified membranes exhibit reduced pore sizes, enabling effective size-sieving effects. Additionally, the IL enhances CO₂ affinity within the COF channels, achieving excellent CO₂ separation performance. Pil J. Yoo and colleagues proposed incorporating ZIF-8 into COF pores and doping with IL/LiTFSI to form a composite IL@MC QSSE²⁵. Physical impregnation is also a common method for introducing ILs into MOF materials. Duan and co-workers successfully prepared IL@MOF composites using IL ([C₂mim][Tf₂N]) and MOF-808 via an in-situ impregnation method²⁶. As shown in Fig 3b, FT-IR spectroscopy confirmed the successful loading of [C₂mim][Tf₂N] onto the MOF-808 framework, showing characteristic peaks for C-F and S=O bonds. The XRD patterns in Fig 3c demonstrate that the composite retains the MOF-808 crystal structure, though the peak intensities decrease with increasing IL loading, indicating effective IL entry into the pores. Nitrogen adsorption

tests in Fig 3d show typical Type I microporous structures and H4-type hysteresis loops, with specific surface area decreasing regularly with increasing IL loading, further confirming the successful filling of IL into MOF pores. Fig 3e illustrates the preparation process. Besides physical impregnation, capillary action is another common method for introducing ILs into reticular materials, utilizing the porous structure and capillary effects of reticular materials. For example, Yin and co-workers, in constructing photocatalytic nanoreactors, confined ILs within COF nanopores via capillary effects under vacuum, forming IL-confined COF composites (Fig 3f). This method enables precise control over the distribution of ILs within COF channels, allowing for performance tuning²⁷. Additionally, Deng and co-workers confirmed the role of ILs in tailoring the layer stacking of 2D COFs via physical impregnation, facilitating further exploration of stacking-mode-dependent applications (Fig 4a).

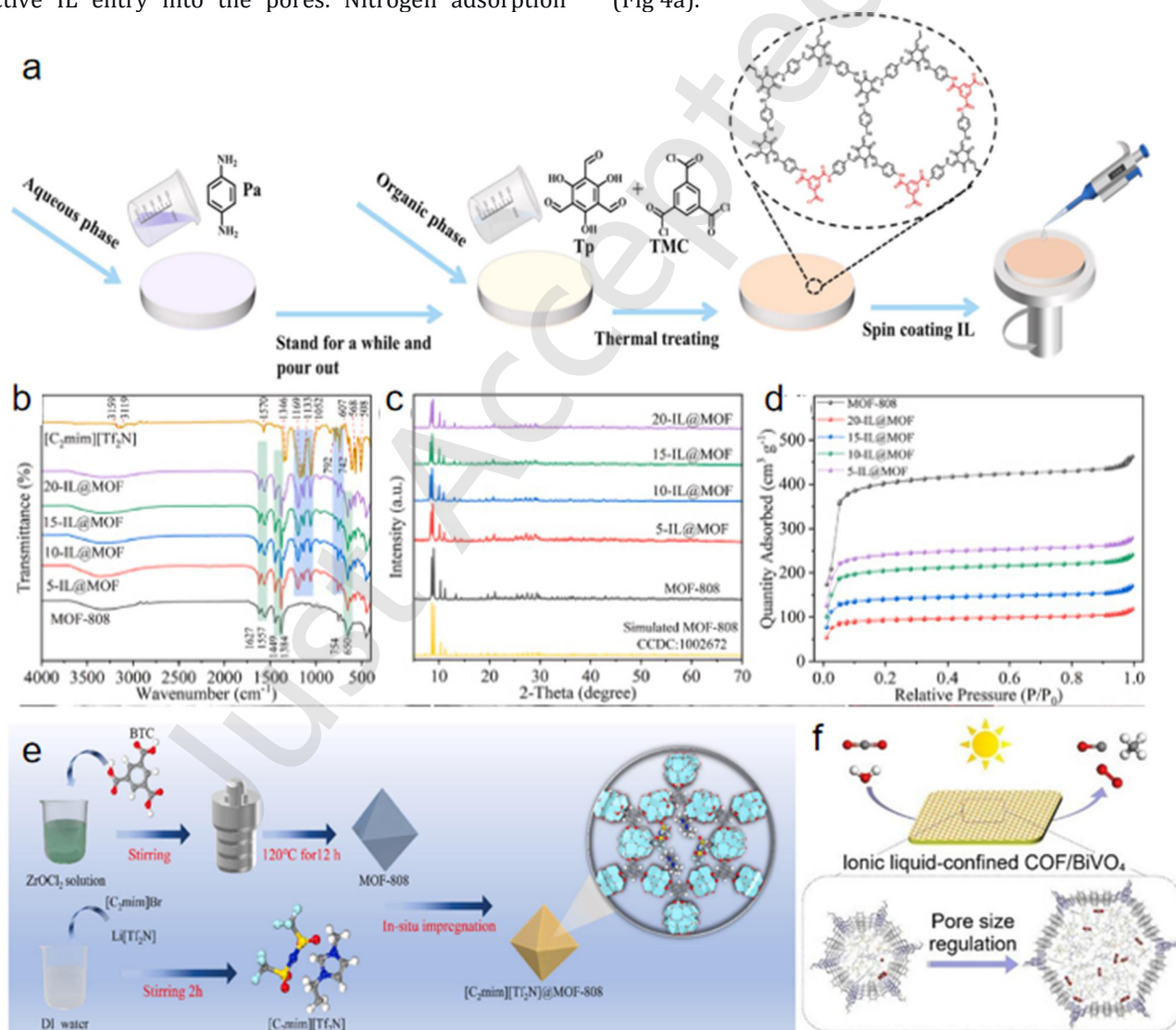


Fig3. (a) Schematic diagram of the preparation process for the IL@TpPa-TMC/PSF composite film.²⁸ Copyright 2024, The Authors, published by Elsevier. (b) Fourier-transform infrared spectra (c) X-ray diffraction patterns (d) N₂ adsorption-desorption isotherms of the samples; scanning electron microscope images. (e) Scheme for the Preparation of [C₂mim][Tf₂N]@MOF-808.²⁹ Copyright 2025, The Authors, published by Elsevier. (f) Ionic-Liquid-Confined Covalent Organic Framework Pores as Carbon Monoxide Nanoreactors for Light Conversion.³⁰ Copyright 2025, The Authors, published by John Wiley and Sons.

The advantage of physical introduction lies in its universal applicability, being suitable for most combinations of reticular materials and ILs without requiring complex synthetic design. Additionally, it generally does not disrupt the original crystal structure and pore integrity of the reticular materials³¹. However, because the interactions between ILs and reticular materials are primarily weak physical forces (e.g., van der Waals forces, hydrogen bonds), ILs are prone to leakage and loss during subsequent applications (e.g., catalysis in liquid media, washing) or under vacuum conditions. Furthermore, the distribution of ILs within the pores may be uneven, leading to local aggregation. Therefore, in specific reactions, covalent bonding is required to introduce ILs into reticular materials to enhance their stability in subsequent applications.

2.1.2 Chemical Introduction (Covalent Post-Synthetic Modification):

Unlike physical impregnation, covalent post-synthetic modification is a strategy that anchors ILs firmly onto the reticular framework via chemical bonds. In COF materials, this introduction strategy primarily involves first synthesizing COF precursors bearing reactive sites (e.g., amino, aldehyde, or hydroxyl groups), followed by chemical reactions between these sites and ILs bearing complementary functional groups to achieve covalent grafting of ILs³². Through chemical reactions, IL functional groups are covalently attached to COF materials, thereby imparting new properties or improving existing ones. Zhang and co-workers synthesized a series of imine-linked triazine COFs ([HO]X%-TAPT-COFs) with π -stacking and appropriate pore sizes and prepared a series of [AelmBr]X%-TAPT-COFs by chemically integrating amino-functionalized imidazolium IL (1-aminoethyl-3-ethylimidazolium bromide, [Aelm][Br] (NH₂-IL)) onto the channel walls of [HO]X%-TAPT-COFs. This work achieved efficient CO₂ capture and conversion via chemical grafting of amino-functionalized imidazolium IL onto COF channel walls (Fig 4b), providing new insights for the targeted design of COF-based composites for CO₂ capture and conversion³³. Li and co-workers constructed COF-PolyILs composites by grafting imidazolium-based poly (ionic liquids) onto COF frameworks via vinyl polymerization. The abundant imidazolium sites enhanced the stability of the COF-polyILs composites in high-salinity and high-acidity solutions. This covalent attachment strategy enhances the stability of functional sites within COFs, showing promise for nuclear waste treatment and environmental remediation³⁴. Furthermore, COFs are considered promising hydroxide-conducting materials due to their highly ordered crystalline porous structures and tunable functionalities. However, the lack of hydroxide-conducting functional groups on COF backbones limits their further development in anion-exchange membrane fuel cells (AEMFCs). Currently, IL impregnation is employed to address this issue, but IL leakage under operating conditions remains a challenge. To further address potential IL leakage during introduction, Tang

and co-workers grafted guanidinium-based ILs onto COF channel walls via Williamson ether synthesis and then doped them into guanidinium-functionalized poly (2,6-dimethyl-1,4-phenylene oxide) (GPPO) to prepare IL-COF/GPPO composite membranes. The ILs grafted onto COF nanochannels serve as "active sites" on the membrane, enhancing hydroxide ion migration rates and thus improving conductivity. The material, doped as a filler into anion-exchange membranes, significantly improves hydroxide ion migration rates and conductivity while addressing IL leakage, providing high-performance membrane materials for fuel cells³⁵. Wu and co-workers covalently anchored flexible poly (ionic liquids) onto vinyl-functionalized COF pore walls via photo-initiated copolymerization to prepare COF-PIL hybrids (COF- β -PIL and COF- γ -PIL). The incorporation of PIL into the COF endowed the COF- γ -PIL hybrid with porous framework characteristics, showing significant effectiveness in promoting mass transfer of polybrominated diphenyl ethers (PBDEs), facilitating reliable environmental detection and assessment of trace PBDEs³⁶. Covalent post-synthetic modification also finds widespread application in IL introduction into MOFs. Li and co-workers successfully grafted ILs onto MIL-88(Fe)-NH₂ via post-synthetic modification to prepare a novel composite adsorbent MIL-88(Fe)-NH₂/IL (Fig 4c)³⁷. Hu and co-workers successfully prepared ILs-NH₂-MIL-88B composite supports via a four-step process on NH₂-MIL-88B: CDI activation, 1-(3-aminopropyl) imidazole grafting, bromoethanol quaternization, and NaBF₄ ion exchange. The obtained materials were characterized by FT-IR, XRD, and TG (Figs 4d, 4e, 4f). FT-IR spectra showed typical C-H stretching vibration peaks at 2920 cm⁻¹ and 2852 cm⁻¹ after IL modification, confirming successful IL grafting; after laccase immobilization, characteristic laccase peaks and amide I bands appeared at 1060 cm⁻¹ and 1635 cm⁻¹, confirming successful laccase loading on the support surface. XRD patterns indicated that the characteristic diffraction peak positions and intensities of NH₂-MIL-88B remained essentially unchanged after IL modification, indicating that the modification process did not disrupt the MOF crystal structure. TG curves showed significant weight loss corresponding to IL component thermal degradation in the 200–400°C range for ILs-functionalized supports, and laccase protein thermal degradation features in the 100–300°C range after immobilization, further confirming the successful introduction of ILs and laccase. This study successfully constructed an efficient laccase immobilization platform based on IL-functionalized MOFs. The organic integration of ILs and MOFs effectively preserved the native spatial conformation of laccase while significantly enhancing its environmental adaptability and structural stability, providing solid experimental support for the design of high-performance, long-life immobilized enzyme biocatalysts³⁸. Shu and co-workers combined 1-butyl-3-methylimidazolium bisulfate (BMImHSO₄) IL with MOF-808 via coordination interactions to construct BMImHSO₄@MOF-808 porous composites. This IL modification of MOF fully leveraged the advantages of both materials in oxygen transport and proton conduction while effectively overcoming the poor proton

conductivity of MOFs and the easy leaching of ILs³⁹.

Compared to physical impregnation or capillary action, covalent post-synthetic modification offers higher stability due to covalent bonds, ensuring IL components are resistant to leaching even under harsh conditions. Moreover, the degree of post-modification and the choice of IL structures allow precise control over composite

properties⁴⁰. Pre-designing active sites on the framework also enables high-density, uniform IL immobilization. However, covalent post-synthetic modification involves cumbersome synthetic steps requiring multiple reactions, including reticular material synthesis, post-modification, and possible ion exchange. Moreover, harsh post-modification reactions may reduce the crystallinity of reticular materials or block pores, thereby damaging the crystal structure.

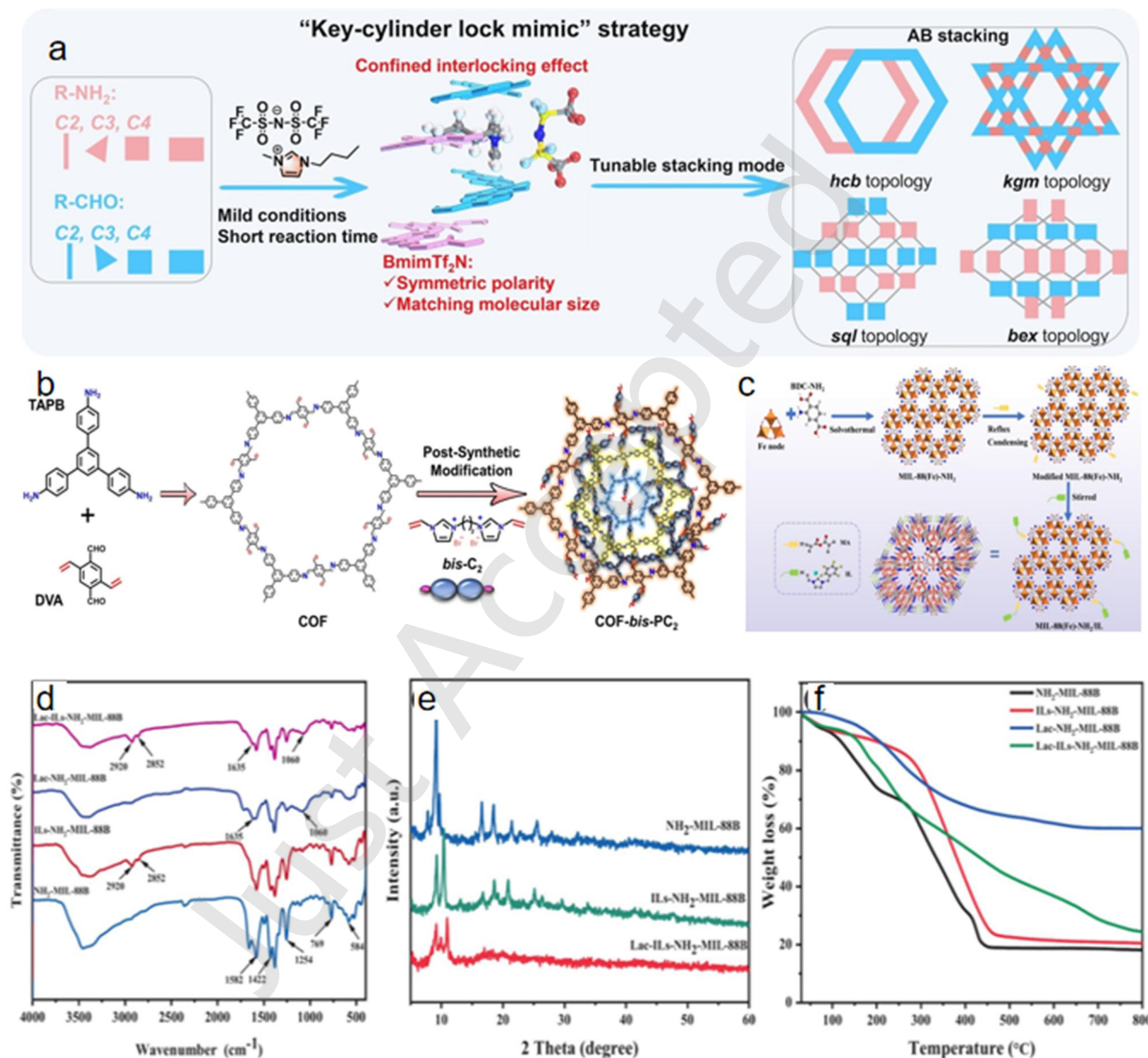


Fig4.(a)Accelerating the Growth of Covalent Organic Frameworks via Adjustable Layered Ion Liquid Overlays.⁴¹ Copyright 2024, The Authors, published by John Wiley and Sons. (b) COF-double PC₂ composites were prepared by post-synthesis modification of covalent organic frameworks using polyisoprene via a graft polymerization method.⁴² Copyright 2022, The Authors, published by American Chemical Society.(c) Synthesis and structural schematic of MIL-88(Fe)-amino/IL materials.⁴³ Copyright 2025, The Authors, published by Elsevier. (d)FT-IR spectra of carrier and immobilized laccase (e) XRD patterns (f) TG curve of carriers and immobilized laccase.⁴⁴ Copyright 2026, The Authors, published by Elsevier.

2.2 Roles of Ionic Liquids in the Synthesis of Reticular Materials:

2.2.1 As Solvents/Templates:

During the synthesis of reticular materials, ILs are used as reaction media (solvents). On one hand, the high polarity and low vapor pressure of ILs can promote the crystallization of reticular materials⁴⁵. On the other hand, during crystallization, IL molecules may become

encapsulated within the pores of the reticular material, or their cations/anions may interact electrostatically with charges/functional groups on the framework, thus becoming retained in the final product⁴⁶. He and co-workers reported an IL strategy (Fig 5a) for preparing uniform MOF nanocrystals by introducing competitive coordination, leveraging the dynamic nature of coordination bonds to improve upon current synthetic approaches⁴⁷. This study demonstrated a novel, facile strategy for preparing approximately 10 nm MOF nanocrystals by introducing competitive coordination between MOFs and IL acetate ions (OAc^-). The resulting MOF nanocrystals exhibited significantly enhanced gas adsorption kinetics, injecting new vitality into the gas adsorption field. Additionally, Han and co-workers designed imidazolium IL solutions and electrochemically treated them to obtain solutions containing stable imidazolium radicals. Precursors were directly added to these solutions, yielding products with stirring at room temperature (Fig 5b)⁴⁸. This work altered MOF synthesis kinetics via solution chemistry, proposing a new radical-assisted MOF synthesis route (Fig 5c) that enables rapid or even instantaneous synthesis of various MOFs at room temperature. Sang and co-workers confirmed these findings, using $[\text{Omim}]\text{Cl}$ as a solvent to synthesize UiO-66 at room temperature in just one hour. Compared to the traditional solvothermal method using DMF (requiring 120 h), this method reduced the reaction time by over 100-fold! Unlike the conventionally synthesized $\text{Zr}_6\text{O}_4(\text{OH})_4(\text{BDC})_6$, which suffers from ligand defects, the authors speculated this may be due to room-temperature synthesis and rapid crystallization. TEM monitoring during the reaction (Fig 5d) revealed continuous crystal growth, reaching approximately 80 nm after 1 hour⁴⁹. Zhao and co-workers reported a green and efficient synthesis method for two-dimensional keto-enamine-linked COFs. Using ILs as solvents, all COF precursors were mixed in ILs, degassed under liquid nitrogen, and kept at 120°C for 3 days. Testing showed no unreacted groups remained⁵⁰. To further investigate the effect of IL anions on the crystalline structure of COFs, Jiang and co-workers used ILs with different anions as reaction solvents to synthesize a series of two-dimensional imine-linked COFs. Experimental results demonstrated that the orthorhombic space group structures of the two COFs prepared via ionothermal methods were more stable. Overall, ILs serve as environmentally friendly solvents while facilitating the formation of COF crystals, potentially acting as substitutes for traditional solvents during synthesis⁵¹. This strategy is also applicable to COF materials. Yu and co-workers used the common IL BmimTf_2N as a solvent and mediator, optimizing reaction conditions to achieve COF-TAPT-Tf@ BmimTf_2N synthesis in 30 minutes with a 90% yield. This study achieved precise control over the layer stacking mode of COFs, providing new insights for the structural design of 2D materials. Xu and co-workers elucidated the role of ILs in COF synthesis, analyzing the mechanisms and advantages with specific case studies⁵².

Chen and co-workers proposed a trace IL (2 μL)-mediated one-step aqueous-phase synthesis strategy for

designing enzyme@COF biocatalysts. This strategy requires no organic solvents, relying solely on environmentally friendly and biocompatible aqueous media, effectively overcoming the incompatibility between COF crystallization conditions and native enzymes. The highly crystalline COF pores provide sieving effects, imparting non-native biocatalytic selectivity to some enzyme molecules; simultaneously, integrating COF chemical properties with enzyme biological functions constructs a high-performance self-cascading photo-enzyme reactor, significantly enhancing pollutant degradation efficiency. This work provides a mild, green strategy for designing stable, high-activity biocatalysts⁵³.

The advantage of using ILs as solvents/templates lies in their potential role as structure-directing agents, promoting the formation of specific topologies. Additionally, ILs confined in nanopores may exhibit unique properties distinct from their bulk state. However, the mechanism of action (solvent vs. template) is sometimes difficult to clearly distinguish. Furthermore, IL usage is often large and costly, requiring recovery and presenting operational challenges.

2.2.2 Structure-Directing Agents:

Both reticular materials and ILs are hailed as "designable materials." Reticular materials offer precise topological structures and permanent pores, while ILs provide rich physicochemical properties and tunable solubility⁵⁷. Combining them aims to create a synergistic "1+1>2" effect. Therefore, efficiently, stably, and orderly introducing ILs into reticular materials to impart new functions, with practical function guiding the structural design of IL-reticular material composites, becomes a core challenge. Furthermore, the layer stacking mode of 2D reticular materials critically determines their optoelectronic properties and mass transport behavior⁵⁸. ILs play a role as structure-directing agents in this process. Multiple non-covalent interactions between ILs and the reticular framework can guide the spatial orientation of monomers during polymerization, thereby affecting the stacking mode and pore structure of the final product. Studies have shown that IL-mediated structural regulation of COFs primarily involves selecting ILs with different cation/anion combinations to precisely control interlayer interactions in COF materials, enabling switching between different stacking modes. This provides a new degree of freedom for tuning the electronic properties and mass transport behavior of COFs. Cai and co-workers modified and prepared COF materials via stepwise post-synthetic modification, obtaining modified COFs through quaternization reactions with ILs. Characterization confirmed that ILs occupied the pores, reducing crystallinity. Moreover, flexible post-synthetic modification of COFs enriches the variety of COF-IL composites⁵⁹. Zhang and co-workers prepared a novel linear poly (ionic liquid)-modified COF composite via a bottom-up approach, grafting functional groups onto monomers before COF synthesis to precisely control the location and number of active sites, further ensuring functionalization. To achieve controlled stacking modes in

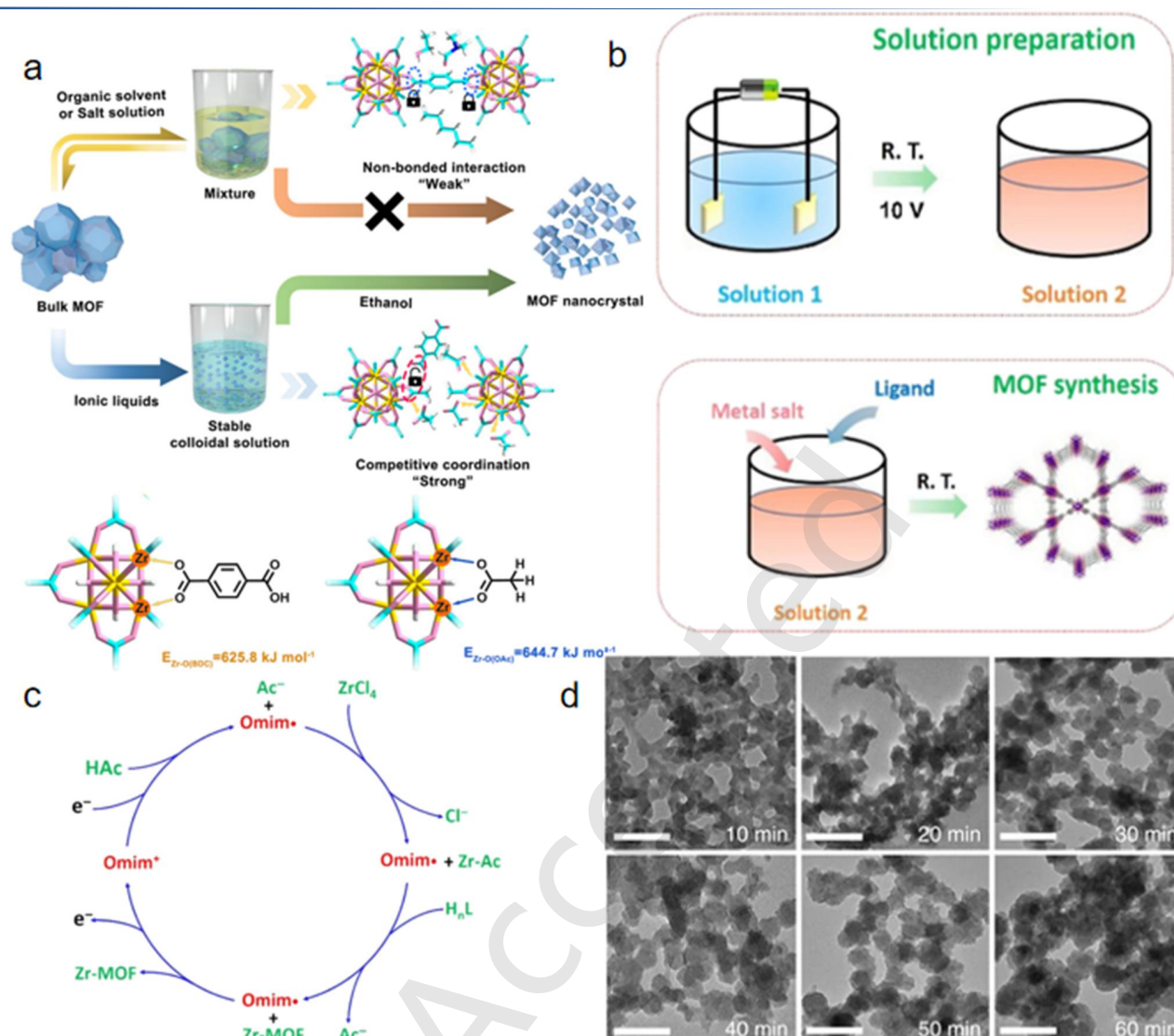


Fig5. (a) Schematic diagram of the preparation of MOF nanocrystals and the CCIE process in an ionic liquid. The yellow symbols represent the attractive interaction between acetate ions and zirconium ions.⁵⁴ Copyright 2025, The Authors, published by John Wiley and Sons. (b) Schematic diagram of MOF synthesis in a free radical solution. (c) A Route for the Radical-Assisted Synthesis of Zr-MOFs Using Omim+.⁵⁵ Copyright 2022, The Authors, published by Chinese Chemical Society. (d) TEM images of the products synthesized in [Omim]Cl with different reaction time.⁵⁶ Copyright 2017, The Authors, published by Springer Nature.

COFs, we performed density functional theory (DFT) calculations (Fig 6a), confirming that the introduction of triazolium ILs and quinoline linkages renders the framework highly electron-deficient. Furthermore, π -bridge-linked ionic COFs significantly narrow the band gap and enhance intermolecular charge transfer. Optimization of molecular planarity further regulates molecular stacking between frameworks to enhance interlayer charge hopping⁶⁰. Spectroscopic studies and molecular dynamics simulations (Figs 6b and 6c) further revealed ion-specific adsorption phenomena within the framework, where the introduction of triazolium ILs enhances anion confinement, optimizing the solvation structure during electrode reactions and resulting in faster reaction kinetics. ILs as structure-directing agents for MOFs primarily manifest in dissolving precursors, regulating crystal nucleation and growth, and shaping the pore structure of the final product⁶¹. Sun and co-workers synthesized a polyethylene glycol (PEG)-functionalized dicationic aliphatic IL and applied it for the first time to

fabricate HP-MOFs (Fig 6d). PDAB-IL exhibits high fluidity, acting as both solvent and surfactant, capable of dissolving MOF precursors and directing their crystallization, thereby effectively avoiding the involvement of other media⁶². Shang and co-workers first reported the synthesis of La-MOFs with different morphologies using an $\text{H}_2\text{O}/\text{BmimPF}_6/\text{TX-100}$ IL microemulsion system, indicating that the morphology of dispersed droplets in the microemulsion strongly influences the morphology of MOF crystals. This work pioneered a method for controlling MOF morphology via IL microemulsions⁶³. Yu and co-workers successfully synthesized nanoscale MOFs using a quaternary IL microemulsion system. By adding ethanol to the $\text{H}_2\text{O}/\text{BmimPF}_6/\text{TX-100}$ mixture, they improved the solubility of poorly soluble organic ligands in water, allowing MOFs to nucleate and grow within droplets, achieving nanoscale MOF preparation. However, this method still requires triethylamine as an additive to promote ligand deprotonation, significantly increasing the use of organic solvents in the overall synthesis process⁶⁴.

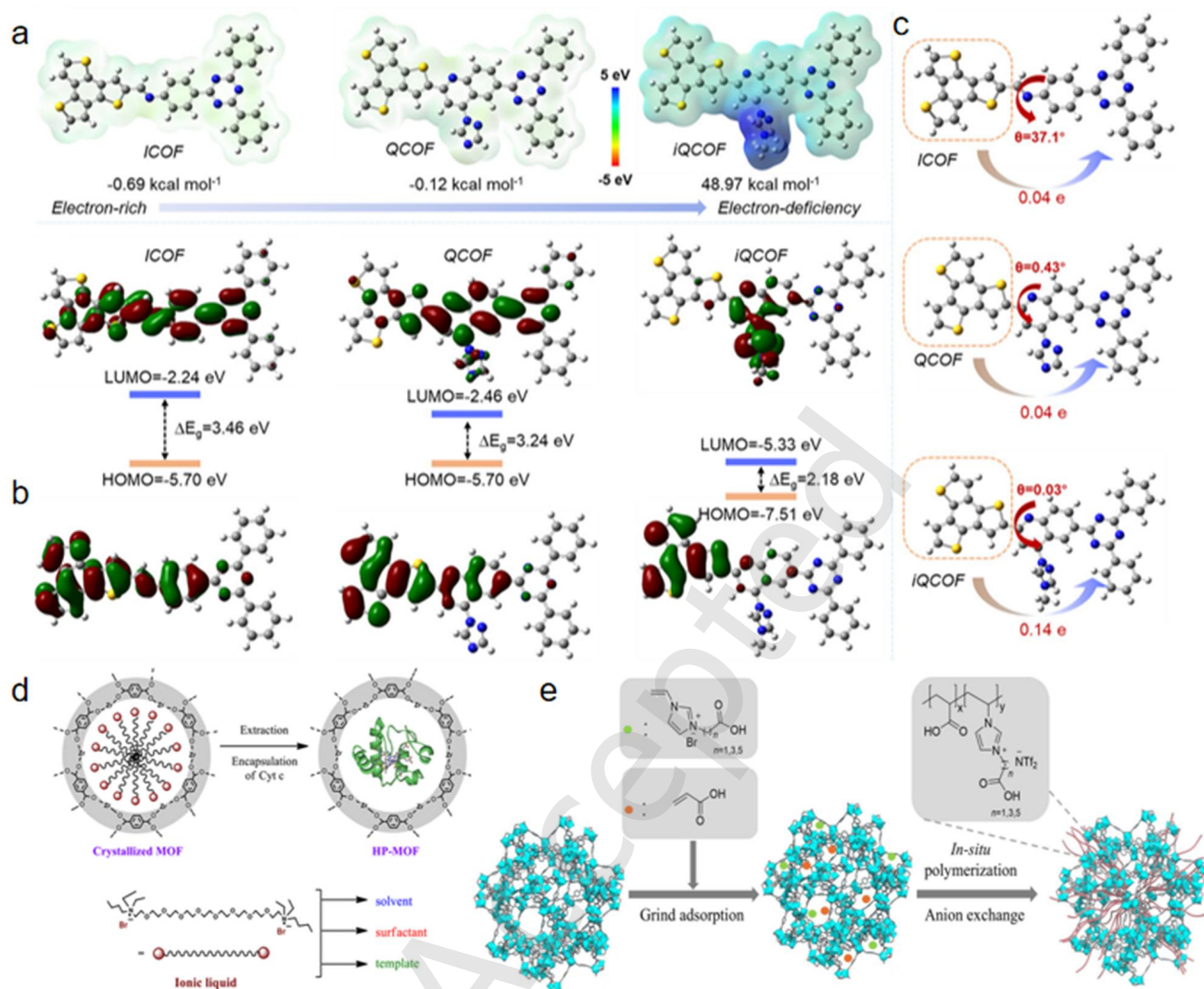


Fig6. (a) Analysis of the electrostatic potential distribution shows the overall averages for ICOF, QCOF, and iQCOF, revealing the electron-deficient nature of iQCOF. (b) HOMO-LUMO energy gaps for the repeating units. (c) The relationship between the charge transfer number and the dihedral angle for ICOF, QCOF, and iQCOF, indicating that iQCOF exhibits superior charge transfer performance.⁶⁵ Copyright 2025, The Authors, published by John Wiley and Sons. (d) This schematic illustrates the nucleation process of the framework structure surrounding PDAB-IL molecules: these molecules exist in the form of micelles and exert a templating effect through electrostatic interactions with the precursor substance.⁶⁶ Copyright 2022, The Authors, published by American Chemical Society. (e) Synthesis Process of Poly(IL-AA)@MIL-101(Cr)⁶⁷. Copyright 2024, The Authors, published by Elsevier.

2.3 Property Regulation:

In summary, introducing ILs into reticular materials represents a highly promising function-oriented structural strategy. Through the flexible application of ionothermal synthesis, post-synthetic modification, and structure-direction, the excellent properties of ILs can be precisely "encoded" into the highly ordered nanopores of reticular materials, creating novel multifunctional materials with outstanding performance. This strategy successfully expands the application boundaries of reticular materials in key areas such as energy, environment, and catalysis. Future research will increasingly focus on in-depth understanding of structure-property relationships, simplification and scale-up of preparation processes, and innovative design tailored to practical demands, driving IL-reticular materials from the laboratory toward industrialization.

The introduction of ILs profoundly impacts the pore structure, stability, and electrical conductivity of reticular material composites.

2.3.1 Pore Structure Regulation:

The introduction of ILs typically leads to a decrease in the specific surface area and pore volume of composites, an inevitable consequence of IL molecules occupying pore space. However, this "sacrifice" is acceptable in certain applications—because while occupying pore space, ILs also endow reticular materials with new functionalities.

ILs modulate MOF pore structures primarily through two pathways: "guest filling" and "surface modification,"

enabling precise control over pore size, pore microenvironment, and pore accessibility, with broad applications in gas separation, catalysis, and solid-state electrolytes. Uzun and co-workers introduced a new concept of core-shell IL-MOF composites, depositing the hydrophilic IL 1-(2-hydroxyethyl)-3-methylimidazolium dicyanamide ([HEMIM][DCA]) onto hydrophobic zeolitic imidazolate framework ZIF-8. The presence of IL within MOF cages enhanced the selectivity of MOFs for different gas separations by occupying a significant portion of the pore space. When IL is deposited on the external surface of ZIF-8, as shown in this study, the MOF pore space remains available for gas adsorption, suggesting the superiority of core-shell IL-MOF composites in gas separation processes⁶⁸. Pei and co-workers constructed ionic ultramicroporous MOFs (IUM-MOFs) with high CO₂ affinity by modulating the pore microenvironment of UM-MOFs using functional ILs with specific moieties, applying them to CO₂/CH₄ separation, achieving efficient capture of CO₂ from biogas via adsorption⁶⁹. ILs also effectively regulate the pore structure of COFs. Wang and co-workers modified COF-polyamide layers with imidazolium ILs; this IL modification effectively reduced the pore size of COFs and increased their CO₂ affinity, opening new avenues for preparing and applying interfacially polymerized COF membranes for gas separation. Li and co-workers investigated the He/CH₄ separation performance of fumaramide-based covalent triazine framework (CTF-FUM) COF membranes coated with different ILs. Results indicated that longer cation chains promote more uniform IL distribution and more effective filling of COF pores, thereby further suppressing CH₄ transport. Anion size also plays a key role, with bulkier anions more effectively occupying COF pores and enhancing He/CH₄ separation performance. These findings provide a molecular-level understanding of gas transport in IL-coated COF membranes and highlight their potential for efficient helium recovery⁷⁰.

ILs play a crucial role in modulating the pore structure of reticular materials, primarily through mechanisms such as spatial confinement, interlayer stacking regulation, and pore size/channel modification, thereby significantly improving COF crystallinity, porosity, and functional performance.

2.3.2 Stability Regulation:

The introduction of ILs can significantly enhance the chemical and thermal stability of reticular materials. Multiple non-covalent interactions (electrostatic, hydrogen bonding, π - π stacking, etc.) between ILs and the reticular framework act as "molecular glues," enhancing the overall structural integrity. IL coating on MOF surfaces or modification within MOF pores can optimize the support surface microenvironment, tune hydrophilicity/hydrophobicity and interfacial interactions, gently maintain the native spatial conformation of MOFs and loaded molecules (e.g., enzymes), and prevent conformational rigidity or structural damage caused by strong interactions. For

instance, Hu and co-workers successfully constructed an efficient laccase immobilization platform based on IL-functionalized MOFs. The organic integration of ILs and MOFs effectively preserved the native spatial conformation of laccase while significantly enhancing its environmental adaptability and structural stability³⁸. Meanwhile, Zeng and co-workers, via impregnation-grinding-in situ polymerization{Fig6e}, loaded poly(ionic liquid-acrylic acid) onto the surface and pores of MIL-101{Cr}, retaining the MOF crystal structure while improving thermal stability⁷¹. Furthermore, Yang and co-workers successfully developed an IL-stabilized molybdenum-based MOF liquid catalyst for efficient, selective oxidative desulfurization at room temperature, combining high activity, stability, and easy recyclability, offering a promising solution for green fuel desulfurization technology⁷². ILs provide multidimensional stability enhancement for COF materials through synergistic effects such as coordination protection, hydrogen bond reinforcement, interface binding optimization, and interfacial shielding, effectively addressing bottlenecks such as hydrolysis susceptibility, leakage, and aging in practical applications (e.g., gas separation membranes, catalysis, adsorption). Wang and co-workers achieved enzyme-like Zn-OH chemisorption in a fluid environment by combining a Zn²⁺-coordinated COF framework with hydroxyl-functionalized ILs. The hydroxyl groups of the ILs can coordinate with Zn²⁺ metal nodes in the COF framework, generating stable coordination structures (e.g., Zn-OH) in situ, effectively protecting the active centers of the COF framework and maintaining structural integrity under strong acid, strong base, or humid conditions, thereby significantly enhancing chemical stability⁷³. ILs, through their unique physicochemical properties (e.g., low volatility, high thermal stability, tunable solvation ability) and flexible molecular design, play a key role in enhancing the stability of reticular materials (e.g., ionogels, nanoconfined membranes, low-dimensional electronic materials).

2.3.3 Ionic Conductivity Regulation:

When discussing conductive properties, it is essential to first distinguish between two fundamentally different conduction mechanisms: electronic conduction, which relies on the transport of free electrons or holes through the band structure of a material and is typically related to the material's electronic band structure and charge carrier mobility; and ionic conduction, which depends on the directional migration of ions through a medium, with conductivity governed by factors such as ion concentration, ion mobility, and temperature.

ILs inherently possess high ionic density and ionic conductivity. Encapsulating (filling) them within the micropores of reticular materials directly provides the composite with a highly conductive medium, significantly reducing the overall impedance of the composite. Based on this understanding, this section focuses on the regulation of ionic conductivity in IL/reticular material

composites and their applications in solid-state electrolytes. Guo and co-workers prepared Ni-MOF materials using Ni as the central metal ion and 2-methylimidazole as the ligand (Fig 7a). Subsequently, they encapsulated highly conductive 1-ethyl-3-butylimidazolium perchlorate (IL) into Ni-MOF (IL@Ni-MOF) to enhance the performance of the composite catalyst and improve the ignition delay time of the ECSP. The conductivity of IL-modified MOFs was significantly improved, demonstrating the potential of manufacturing composite fuels with enhanced conductivity and electrocatalytic performance⁷⁴.

Yoshida and co-workers, for the first time, achieved control over the ionic conductivity of ILs encapsulated in MOF micropores through chemical modification of MOF ligands. By chemically modifying MOF ligands while maintaining the pore structure, they precisely tuned the ionic conductivity of the encapsulated ILs, opening a novel approach for designing new solid-state ionic conductors⁷⁵. He and co-workers synthesized sulfonated COFs via in situ synthesis as multifunctional crosslinkers in poly (vinylidene fluoride-co-hexafluoropropylene) ionogels.

1-Butyl-3-methylimidazolium bis(trifluoromethanesulfonyl)imide ([BMIM][TF₂N]) serves as the IL, providing ionic conductivity and a medium for ion transport. The intrinsic ion nanochannels provide efficient pathways for ion transport, while the negatively charged sulfonic acid groups promote directional cation migration, substantially increasing ionic conductivity⁷⁶. Chu and co-workers encapsulated ILs into the nanopores of UIO-66 to form Li-ILs@UIO-66 composites, which were then dispersed into a PVDF-HFP polymer matrix to form a continuous ion transport network. This system exhibited an ionic conductivity of $4.3 \times 10^{-4} \text{ S cm}^{-1}$ at room temperature and a wide electrochemical window of 4.8 V⁷⁷. Through these mechanisms, IL-modified reticular materials demonstrate significant performance improvements in solid-state electrolytes, electrocatalysts, and other applications, for example, achieving ultra-high ionic conductivity and excellent wide-temperature-range conductivity stability.

2.4 Mechanistic Analysis of IL Functions in Reticular Material Composites:

From the foregoing discussion, it becomes clear that ILs, being composed of both cations and anions, experience a modulation of their charge distribution when confined within the nanopores of reticular materials, owing to the influence of the pore wall surface chemistry. This confinement gives rise to heterogeneous local electric fields within the channels, the strength and spatial distribution of which can be precisely controlled by selecting appropriate IL cation/anion combinations. Such local electric fields are capable of enhancing the adsorption affinity toward polar gas molecules, thereby improving the separation selectivities of CO₂/CH₄ and CO₂/N₂.

In parallel, the nanopores of reticular materials

(typically <2 nm) impose a physical confinement effect on IL molecules, substantially altering their physicochemical properties. Moreover, the intrinsically ordered nanoporous architectures of reticular materials offer low-energy-barrier, long-range ordered pathways for directional ion migration within the IL phase.

Nevertheless, it must be emphasized that the aforementioned mechanisms do not function independently in practical systems; instead, they coexist and operate in a synergistic manner. This "multi-mechanism synergy" framework provides a theoretical basis for the future rational design of high-performance IL/reticular material composites.

3. Application Progress:

IL/reticular material composites fundamentally change the functional paradigm of traditional porous materials. On the one hand, the rigid reticular framework addresses the pain points of ILs—easy leaching in open systems and poor mechanical strength; on the other hand, the molecular tunability of ILs endows the inert framework with dynamic recognition, self-healing, and ion-conducting vitality. This composite strategy effectively breaks through the performance limitations of single-component reticular materials, achieving "1+1>2" functional integration through interfacial synergy. The combination reconstructs the solid-liquid interface at the molecular scale, optimizing mass transfer and local charge distribution within the pores, and producing significant nonlinear enhancement effects on key performance metrics such as catalytic activity, separation selectivity, and energy storage efficiency. The main application areas and specific applications are as follows:

3.1 Efficient Gas Adsorption and Separation:

IL/reticular material composites, combining the high selectivity and strong affinity of ILs with the large specific surface area and high porosity of reticular materials, show significant advantages in gas adsorption and separation. Their applications primarily include:

1. CO₂ Capture and Separation:

COFs, with high porosity and stability, hold great potential for gas separation. However, achieving precise size-sieving without compromising gas diffusion rates is challenging. Li and co-workers proposed a method for establishing tunable local electric fields in COF channels to achieve efficient CO₂ separation in Pebax-based mixed matrix membranes (MMMs). Through host-guest interactions between COFs and ILs with different charges, local electric fields with varying charge densities were achieved. Notably, the MMM with a positive local electric field achieved optimal CO₂/CH₄ separation performance, with significantly enhanced permeability ($\approx 38\%$) and selectivity ($\approx 99\%$), exceeding the Robeson upper bound. This demonstrates the effectiveness of the local electric

field tuning strategy for CO₂ separation in MMMs⁷⁸.

The inherent porosity and fluidity endow porous liquids (PLs) with unique properties and performance, but their preparation remains challenging due to difficulties in liquefaction while maintaining porosity. Therefore, Huang and co-workers developed a stepwise surface functionalization and ion-exchange strategy to realize a rare example of COF-based porous liquids (COF-PLs) based on flexible COFs. Theoretical calculations and CO₂ adsorption experiments showed that the cavities of COF-301-PL undergo dynamic adjustments with changes in CO₂ pressure. This dynamic expansion effect not only provides additional gas adsorption capacity (7.04 mmol/g at 40 bar) but also facilitates mass transfer of gas molecules during catalysis. Consequently, COF-301-PL exhibited excellent catalytic efficiency in converting CO₂ to cyclic carbonates, with enhancements of 24-fold and 17-fold compared to PEGS and solid COF-301 counterparts, respectively. Optimization of substrate adsorption and mass transfer conditions improved the overall catalytic efficiency. This work provides a new perspective for preparing PLs and their significant potential applications in gas adsorption and catalysis⁷⁹. Additionally, Gu and co-workers selected the thermoresponsive phase-change IL [Emim]PF₆, embedded it into DAAQ-COF pores via in situ synthesis to form IL@DAAQ-COF composites, and then mixed them with PIM-1 to enhance the gas separation performance of PIM-1-based MMMs. This work, for the first time, combined phase-change ILs with COF fillers, successfully breaking through the performance bottleneck of MMMs through the triple effects of pore compression, adsorption enhancement, and thermally activated dispersion, providing valuable references for preparing high-performance MMMs for gas separation⁸⁰. Gurkan's team developed IL/MOF composites containing CO₂-reactive IL (1-ethyl-3-methylimidazolium-2-cyanopyrrolide, [EMIM][2-CNpyr]). Using ZIF-8 with precise pore design as the porous support, the material exhibited high CO₂ adsorption capacity at low partial pressures. The CO₂ capture performance of IL/MOF composites was investigated (Fig 7b). Compared to pristine MOF, the CO₂ capture capacity of IL/MOF composites was significantly enhanced. This substantial enhancement was attributed to strong chemical binding between CO₂ and IL active sites. ¹³C solid-state NMR confirmed that the increased CO₂ uptake originated from chemisorption with the IL⁸¹.

2. Selective Adsorption Separation for Noble Gas Recovery:

IL/MOF composites, by introducing new adsorption sites via ILs that preferentially adsorb gases with higher polarizability (e.g., N₂, O₂) while showing weaker adsorption for light gases like He, can significantly enhance He separation selectivity and yield under ambient temperature, low pressure, and high He concentration conditions. Xu and co-workers combined the porous structure of MOFs and the high selectivity of ILs, using MOF PCN-250(Fe) and the small-volume IL 1-

ethyl-3-methylimidazolium valinate ([C₂mim][Val]) to prepare [C₂mim][Val]@PCN-250(Fe) composites (10 wt% loading) (Figs 7c, 7d) to enhance N₂/He and O₂/He separation performance⁸². This material exhibited significantly enhanced separation selectivity and He yield under ambient temperature, low pressure, and high He concentration conditions. This study provides new materials and theoretical foundations for developing efficient, low-energy He recovery processes. However, the application of IL/reticular material composites in noble gas separation and recovery still requires further expansion.

3. Light Hydrocarbon Separation via Synergistic Size and Affinity:

By constructing IL-modified MOFs, the hierarchical pores of MOFs provide diffusion space, combined with the strong affinity of ILs for specific gases (e.g., C₃H₆), efficient light hydrocarbon separation can be achieved, overcoming mass transfer barriers for larger species. Liang and co-workers proposed a simple strategy to construct yolk-shell nanostructured Z67@PDA porous ionic liquids (YSPIs) with relatively low viscosity for C₃H₆/C₃H₈ adsorption and separation. By controlling the self-etching time and surface functionalization, the core size and morphology of the layered YS-MOFs could be well-controlled. Microcavities were created within various types of MOFs without destroying the parent crystal framework. By combining layered yolk-shell nanostructures with low-viscosity DIL solvents, YSPIs exhibited excellent C₃H₆/C₃H₈ separation performance and fluid properties⁸³.

Overall, CO₂ capture and utilization are key technologies for addressing global climate challenges. IL/reticular material composites demonstrate unique advantages in this field. Facing the strategic demands of global carbon neutrality, efficient CO₂ capture and resource utilization have become critical technological bottlenecks. IL/reticular material composites excel in this area, with their core advantage rooted in the dual enhancement mechanism of "physical confinement + chemical recognition": the crystalline framework provides ordered gas transport channels and high specific surface area, endowing materials with excellent CO₂ adsorption kinetics; meanwhile, designable functional ILs act as selective "molecular switches," significantly enhancing CO₂/N₂ and CO₂/CH₄ separation selectivity by tuning pore sizes and pore wall polarity. Furthermore, this composite strategy achieves microscopic spatial coupling of adsorption enrichment and catalytic activation, offering a highly promising material solution for low-energy, high-turnover CO₂ chemical fixation. IL/reticular material composites also show bright application potential in the adsorption and separation of other gases, and their application scope is expected to expand further in the near future.

3.2 Membrane Separation Applications:

ILs play a crucial role in the preparation and separation performance enhancement of reticular material membranes. In membrane preparation, ILs can serve as solvents to improve film formability and structural regularity. In separation performance, the gas affinity of ILs enhances membrane selectivity and permeability; their high viscosity allows them to remain stable within pores, reducing pore size. Composites exhibit superior performance compared to pristine framework materials in gas storage, adsorption, membrane-based gas separation, (Table 1) and ionic conductivity. In MMMs, the strong interactions between ILs and reticular materials improve filler-polymer matrix compatibility, reducing non-selective defects. Zhang and co-workers combined IL [bmim][Tf₂N] with defective UiO-66-NH₂ to prepare MMMs (Fig 7e). The introduction of IL not only promoted uniform filler dispersion but also enhanced filler-polymer interfacial compatibility while providing effective CO₂ adsorption sites. The open metal sites exposed by defective UiO-66-NH₂ provided more anchoring sites for ILs, improving IL stability within the membrane, and the higher microporosity and hierarchical pore structure provided more transport channels for gas molecules⁸⁴. Zhong and co-workers used molecular simulations to study the effect of functional groups in IL@MOFs on gas adsorption, achieving theory-guided experiments and proposing a research model combining molecular simulation prediction and experimental validation, providing new ideas for developing high-performance MOF-based MMMs. This work suggests that theory-guided experimental synthesis is a feasible approach for rapidly preparing high-CO₂-separation-performance membranes, demonstrating that IL introduction improves MMM separation performance and shows good application potential in gas separation⁸⁵. Meanwhile, in the COF application area, He and co-workers combined iCOF nanosheets with high charge density and large aspect ratio with 1-butyl-3-methylimidazolium tetrafluoroborate ([BMIM][BF₄]) to prepare ultrathin, stable COF membranes with excellent CO₂/N₂ separation performance. As shown in the AFM image (Fig 7f), sCOF exhibits high crystallinity and

the IL leaching issue and significantly improves CO₂/N₂ separation performance, providing a useful reference for advancing gas separation membrane technology⁸⁶. In the pharmaceutical field, Liang and co-workers developed a new strategy called "scraping-assisted interfacial polymerization (SAIP)." This strategy uses ILs as the organic phase instead of traditional organic solvents for IP reactions to achieve green and large-scale production of COF membranes. Based on the SAIP strategy, thin and uniform TpPa COF membranes were prepared in a short time, exhibiting excellent performance in antibiotic desalination. Furthermore, this work achieved scalable, green production of COF membranes, promoting their industrial application in water purification and desalination in the pharmaceutical industry⁸⁷. Xu and co-workers proposed a "monomer-catalyst-biphasic solvent" matching strategy, coupling COSMO-RS thermodynamic predictions, deep learning physical property models, and molecular dynamics simulations to screen 10 Mes-IL biphasic systems from 622 commercial ILs, achieving a leap in interfacial polymerization (IP) from "rapid amorphous" to "controllable crystallization." The resulting TpPa-COF membrane thickness was reduced from 520 nm to 124 nm, pure water permeability increased 337-fold ($0.022 \rightarrow 7.43 \text{ L m}^{-2} \text{ h}^{-1} \text{ bar}^{-1}$), tetracycline/NaCl mixed solution antibiotic rejection >95%, NaCl <10%, with no performance decay after 24 h of continuous operation. This strategy was extended to TpAZo and TpTAPT COFs, confirming its universality⁸⁸. The core value of ILs in reticular material membrane technology lies in their dual role as "structure-building" and "interface-defect-repairing" engines. During formation, ILs improve the dispersibility and film-forming toughness of 2D/3D reticular materials, ensuring highly ordered membrane layers; their viscoelasticity enables atomic-level precise tuning of pore sizes. Especially in MMM systems, ILs, by enhancing the interfacial compatibility between fillers and polymer matrices, completely reverse the selectivity collapse dilemma of traditional MMMs caused by phase separation, making composites exhibit comprehensive application potential far exceeding that of parent framework

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Table1: Performance of composite materials in gas separation

Materials (MOF/COF)/IL	Conditions (Temperature/Pressure)	Performance
Uio-66-NH ₂ /IL ⁸⁴	25 °C/4 bar	CO ₂ /N ₂ selectivity: 26.9
ZiF-8/IL ⁸⁵	25 °C/2 bar	CO ₂ /CH ₄ selectivity: 3.2
COF/IL ⁸⁶	25 °C/2 bar	CO ₂ /N ₂ selectivity: 20.3
COF/IL ⁸⁸	25 °C/4 bar	C ₃ H ₆ /C ₃ H ₈ selectivity: 66

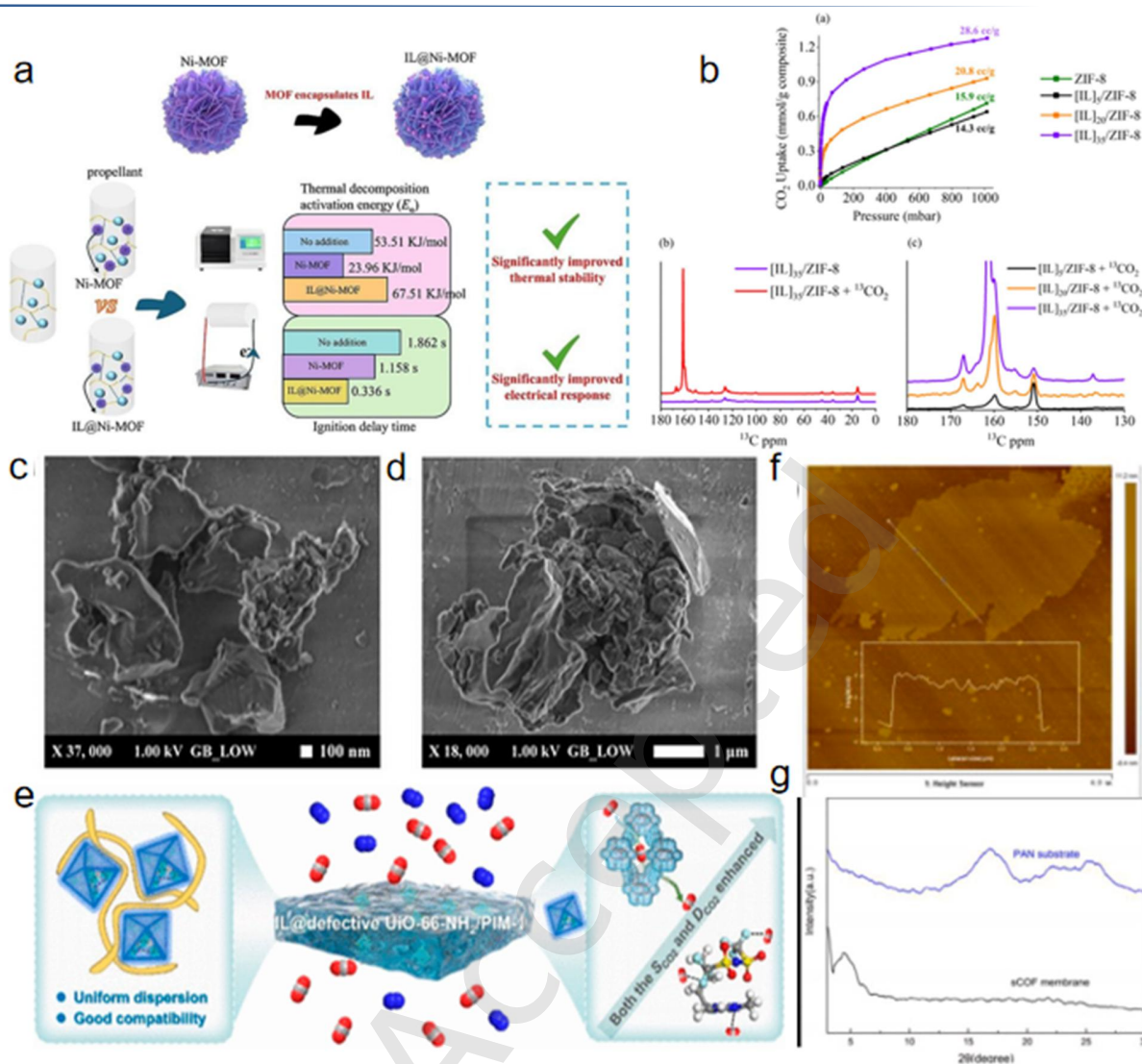


Fig7.(a) Schematic diagram illustrating the steps for preparing MOFs.⁸⁹ Copyright 2024, The Authors, published by Elsevier. (b) Isotherms for carbon dioxide at 30°C for the pristine ZIF-8 and IL/ZIF-8 composite materials. The solid line is provided for reference. Solid-state ¹³C NMR spectrum results for [IL]₃/MOF.⁹⁰ Copyright 2024, The Authors, published by American Chemical Society. (c) SEM images of PCN-250(Fe). (d) [C₂mim][Val]@PCN-250(Fe).⁹¹ Copyright 2025, The Authors, published by John Wiley and Sons. (e) Schematic illustration of a dual-optimization strategy for interface and transport properties of IL-functionalized defective MOFs.⁹² Copyright 2025, The Authors, published by American Chemical Society. (f) Atomic force microscopy image of cCOF nanosheets. The illustration shows the thickness distribution of the cCOF nanosheets along the delineated line. (g) XRD spectra of PAN substrates and sCOF films.⁹³ Copyright 2025, The Authors, published by Elsevier.

3.3 Energy Storage (Solid-State Electrolytes):

In the energy field, IL/reticular material composite systems are becoming a key functional platform for breaking through the performance bottlenecks of conventional electrochemical devices, particularly showing promising application potential in the frontier area of solid-state electrolytes. In solid-state electrolytes, this composite cleverly resolves the long-standing conflict between "ionic conductivity" and "mechanical strength": the periodic open pores of reticular materials (e.g., MOFs/COFs) provide low-energy-barrier directional migration pathways for charge carriers (e.g., Li⁺, Na⁺) in ILs, while the rigid framework endows the material with

excellent dimensional stability and dendrite-penetration resistance, surpassing the low ionic conductivity of traditional polymer electrolytes and the safety concerns of liquid electrolytes.

Jin and co-workers proposed incorporating COF colloids (COF-C) as multifunctional additives into solid polymer electrolytes (SPEs), inhibiting PIL crystal growth, reducing electrolyte crystallinity, and acting as anion receptors to regulate anion coordination, promoting uniform lithium distribution and rapid transport. COF-C also regulates the electrolyte-electrode interface, forming a stable solid electrolyte interphase (SEI), significantly enhancing battery cycling stability and high-rate performance. This study provides a new strategy for designing high-energy-density, high-safety solid-state

batteries, particularly suitable for high-rate charge-discharge and high-active-material-loading scenarios, opening new directions for future electrolyte design⁹⁴. COFs, with their well-defined topologies and tunable pore structures, have become promising cathode materials for high-performance lithium-ion batteries (LIBs). However, their intrinsically sluggish charge transfer and poor reaction kinetics often limit practical applications. To address these issues, Liao and co-workers developed an ionic quinoline-linked COF (iQCOF) cathode material via a one-pot Povarov reaction involving triazolium ILs. The iQCOF structure achieves performance breakthroughs through a triple synergistic enhancement mechanism: π -bridge-induced charge delocalization facilitates charge transport, specific adsorption effects enhance ion-pair dissociation rates, and polar triazine units achieve uniform ion flux to stabilize the interface. Test results show that the iQCOF cathode exhibits a high specific capacity of 407 mAh g⁻¹ (energy density 701 Wh kg⁻¹), excellent rate performance (121 mAh g⁻¹ at 10 A g⁻¹), and only 0.0027% capacity decay per cycle over 10,000 cycles, fully demonstrating its potential as a high-performance organic cathode. This study provides a convenient strategy for developing high-rate COF-based cathodes with fast reaction kinetics, paving new paths for next-generation energy storage technology development⁹⁵. Wang and co-workers proposed an innovative strategy to prepare high-performance quasi-solid-state electrolytes (QSSEs) by confining solvate ionic liquids (SILs) within the nanochannels of methoxy-functionalized COFs (COF-OMe). This design leverages the synergy between ordered COF nanochannels and SILs, enabling QSSEs to exhibit excellent Li⁺ conductivity (1.65×10^{-4} S cm⁻¹ at 25°C) and outstanding thermal stability (up to 150°C). COF-confined SILs effectively lower the Li salt dissociation energy, while pressure-induced alignment of nanochannels achieves uniform Li⁺ flux, suppressing Li dendrite growth. Covalently anchored nanochannels offer significant advantages over physical mixing systems, ensuring structural stability and maintaining long-term cycling performance. Improved electrochemical performance and excellent compatibility with Li metal

anodes indicate the great potential of such QSSEs as advanced electrolyte materials. Furthermore, this strategy is extendable to more architectures and SIL systems, via molecular design and bottom-up preparation, opening new pathways for developing structurally optimized, performance-tailored solid-state electrolytes for high-energy-density Li metal batteries. Zhang and co-workers constructed a novel CPE by encapsulating ILs within amino-functionalized UiO-66-NH₂ MOF nanoparticles and compositing them with a PEO matrix, supplemented by a PAN/PMMA electrospun fiber membrane as a support framework. The researchers systematically analyzed the interfacial behavior and electrode stability of the material. Electrochemical tests (Fig 8a) showed that the PPM-based symmetric battery achieved a critical current density of 1 mA cm⁻², Coulombic efficiency (Fig 8b) increased to 98.4%, and could stably cycle for over 3000 h at 0.1 mA cm⁻², far outperforming the rapid failure of PEO-based batteries (Fig 8c). In situ observations and SEM analysis (Figs 8d and 8e) revealed smooth, uniform Li anode surfaces after cycling, confirming that PPM effectively suppresses Li dendrite growth. XPS results (Fig 8f) showed that the interface layer is rich in inorganic fast-ion conductors such as LiF, Li₃N, and Li₂O, significantly enhancing interface stability and Li⁺ transport efficiency. These results indicate that PPM electrolyte can simultaneously construct stable, high-ion-channel interface phases on both electrodes, comprehensively improving the cycle life and safety of full cells (Figs 8g, 8h). This work developed a novel wide-temperature-range PPM, successfully resolving the inherent conflict between mechanical strength and ionic conductivity in solid-state electrolytes, providing a new strategy for the industrialization of solid-state batteries⁹⁶. Li and co-workers reported a PEO-based composite solid electrolyte (CPE) synergistically enhanced by dual MOFs (MOF-801@808) and ILs for improving solid-state Li metal battery performance. The dual-MOF/IL synergy strategy effectively constructed continuous low-energy-barrier Li⁺ transport channels, significantly enhancing the ionic conductivity and interfacial stability of PEO-based electrolytes⁹⁷.

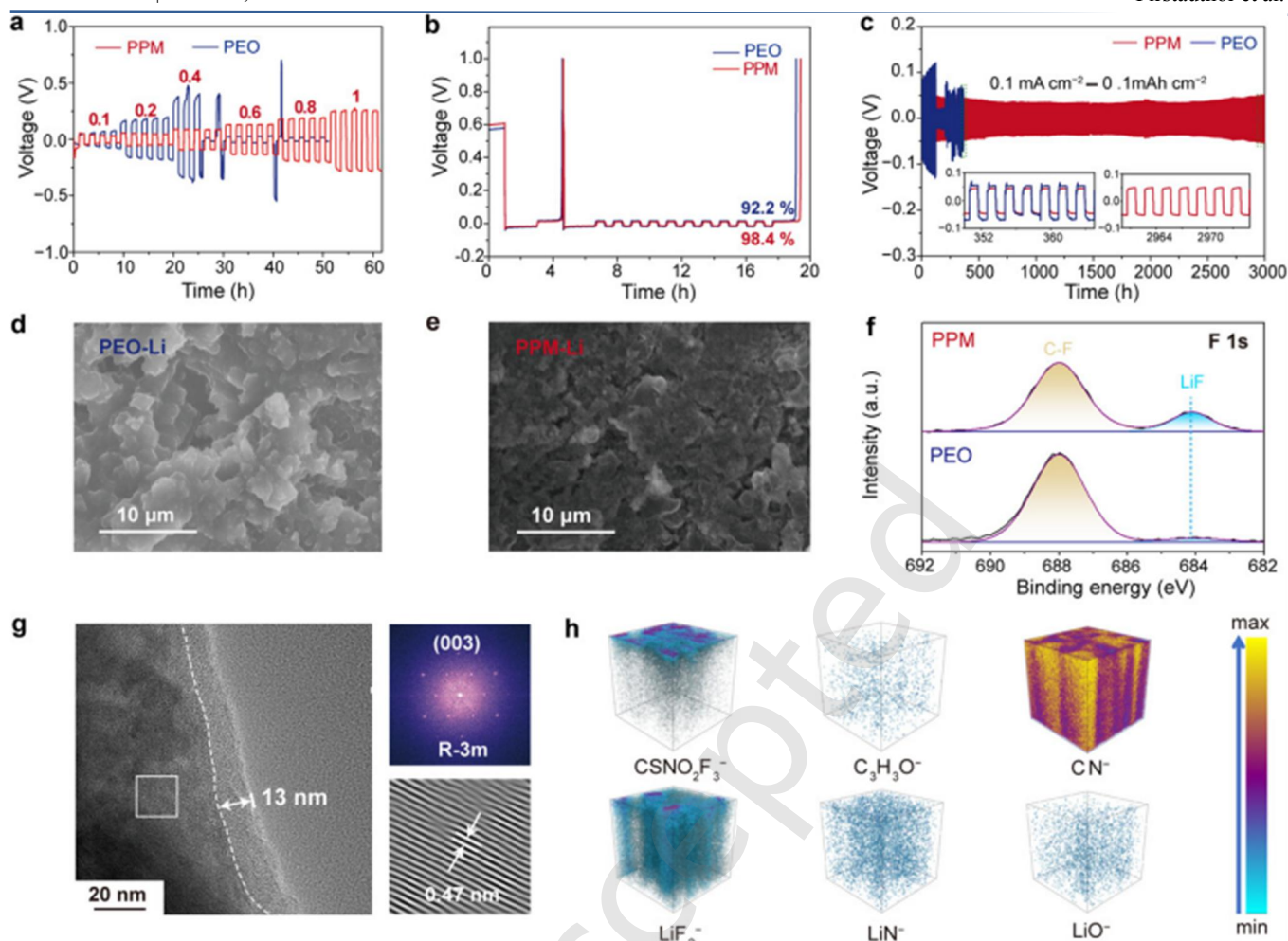


Fig8. (a) Voltage-time curve of a Li||Li symmetric cell with a current density ranging from 0.1 to 1 mA·cm⁻² (b) Coulombic efficiency of a Li||Cu cell tested using the Aurbach method (c) Galvanostatic cycling performance of a Li||Li cell at a current density of 0.1 mA·cm⁻² (0.1 mAh·cm⁻²) at 25°C (d) Scanning electron microscopy (SEM) image of the surface of the cycled lithium anode extracted from a symmetric cell using a polyethylene oxide (PEO) electrolyte (e) SEM image of the surface of the cycled lithium anode extracted from a cycled lithium|PPM|NCM 811 cell using a PPM electrolyte (f) F_{1s} X-ray photoelectron spectroscopy (XPS) spectrum of the cycled lithium anode (g) High-resolution transmission electron microscopy (HRTEM) image of NCM 811 nanoparticles extracted from a cycled lithium|PPM|NCM 811 cell (right side of the image: fast Fourier transform (FFT) pattern and inverse FFT pattern corresponding to the marked area) (h) Three-dimensional view of the spatial distribution of representative fragments of the cycled NCM 811 cathode.⁹⁸ Copyright 2025, The Authors, published by John Wiley and Sons.

Ni and co-workers constructed fast Li⁺ transport channels through weak interactions, demonstrating that weak interactions between carboxyl-functionalized ILs (CIL) and MOFs can regulate ion dynamics, promoting Li salt dissociation to obtain more free Li⁺. Meanwhile, the porous structure of MOFs provides abundant transport channels for Li⁺, further enhancing ionic conductivity. Additionally, these weak interactions promote the formation of LiF-rich SEI, characterized by high chemical stability and low Li⁺ diffusion barriers, facilitating fast charging⁹⁹. The core value of IL/reticular material composites in the energy field lies in the dual optimization of ion transport channels and interfacial chemical environments. In solid-state electrolyte applications, the rigid ion highways provided by the crystalline framework and the high charge carrier concentration endowed by ILs synergistically achieve both high ionic conductivity and wide electrochemical stability windows. This "rigid-flexible" composite material design philosophy is driving a paradigm shift in next-generation high-safety, high-efficiency

electrochemical energy storage and photovoltaic technologies from a material perspective.

3.4 Efficient Catalysis:

Leveraging the synergistic advantages of ILs and reticular materials, this class of composites has been successfully extended to various heterogeneous catalytic reaction systems, including oxidation, C-C coupling, and CO₂ chemical fixation. The broad applicability stems from the dual role of ILs: as an "active source" directly participating in catalytic cycles—for example, halide anions (Cl⁻, Br⁻) act as nucleophiles, synergizing with Lewis acidic sites on the COF framework to efficiently catalyze cycloaddition of epoxides with CO₂. Liao and co-workers, based on Type III porous liquids (Type III-PLs) synthesized from ZIF-8 and IL [PMIm]Br, catalyzed the cycloaddition of CO₂ with styrene oxide at 80°C and 1.0 MPa, significantly enhancing CO₂ conversion by 50.39% and achieving a styrene carbonate (SC) yield of 93.08%¹⁰⁰. ILs also serve as "immobilization platforms," leveraging their highly polar microenvironment to firmly

anchor transition metal complexes (e.g., Pd, Ni, Ru) within MOFs/COFs pores, forming single atoms or sub-nanocluster catalytic arrays. Notably, compared to traditional metal/oxide supports, the ordered pore structure of reticular materials, in synergy with ILs, can regulate substrate molecular diffusion pathways, enabling shape-selective catalysis that reduces side reactions and improves regioselectivity of target products. Wang and co-workers proposed using ILs 1-alkyl-3-methylimidazolium tetrafluoroborates ([Cnmim][BF₄], n = 4, 6, 10) as solvents, suspending triformylphloroglucinol (Tp) and 4,4'-azodianiline (Azo) in them, and stirring at 50°C to construct a series of hierarchically porous COF materials, HP-TpAzo¹⁰¹. HP-TpAzo was stable in organic solvents and acid/base solutions, exhibiting good chemical stability, and began to decompose at 350°C, also showing high thermal stability. By changing the alkyl chain length of the ILs, the COF pore size was tuned. After synthesis, the template ILs were removed. Besides intrinsic micropores, HP-TpAzo also formed large mesopores. HP-TpAzo@Pd, formed by loading Pd, exhibited excellent catalytic activity in Suzuki-Miyaura coupling reactions of substrates of different sizes, especially for large substrates, with yields up to 94%. This is attributed to the layered porous structure of COF materials facilitating mass transport for large compounds. The catalyst maintained good activity after five reuses. This new synthesis method endows COF materials with higher crystallinity, stability, and hierarchical pore structure while significantly shortening synthesis time. This "diversification of active sites" and "ordering of diffusion pathways" superposition makes IL/reticular material composites a highly competitive multifunctional platform in the current heterogeneous catalysis field. The synergistic advantages of ILs and reticular materials have also achieved significant progress in photo/electrocatalysis. Jing and co-workers focused on the nanoconfinement effect of COF pores, constructing IL@COF nanoreactors based on Z-scheme heterojunctions by tuning COF pore sizes. Under full-spectrum pure water conditions, the CO₂ conversion rate was significantly enhanced 38-fold compared to BVO, with 100% selectivity for CO and CH₄ products and effective suppression of H₂ generation. Under 405 nm monochromatic light irradiation, the apparent quantum yield (AQY) reached 12.7%, ranking among the top in similar systems¹⁰².

Furthermore, Huang and co-workers developed a stepwise surface functionalization and ion-exchange strategy to realize a rare example of flexible COF-based porous liquids (COF-PLs). By coating the outer surface of carefully selected 3D flexible COF-301 with imidazolium salts and then using anionic crown poly(ethylene glycol) sulfonate (PEGS) for liquefaction via electrostatic interactions, flexible COF-301-PL was obtained. Optimization of substrate adsorption and mass transfer conditions improved the overall catalytic efficiency. This work provides a new perspective for preparing PLs and their significant catalytic efficiency¹⁰³. COFs, with their periodically connected porous network structures and good biosafety, have been widely used for enzyme

immobilization. This "armor-like" COF framework provides highly permeable enclosed compartments for guest enzyme molecules, offering important ideas for designing stable, highly active novel biocatalysts. The in situ assembly strategy, encapsulating enzyme molecules within the COF framework during crystallization, is an important approach for designing biocatalysts. This technique can integrate relatively large enzyme molecules into small-pore COFs, effectively preventing leaching and facilitating large-scale industrial catalysis applications.

Despite progress in designing enzyme@COF biocatalysts via in situ assembly, significant challenges remain. These mainly stem from the conflict between the harsh crystallization conditions of COFs and the structural fragility of native enzymes. In fact, some recent strategies based on template protection and aqueous-phase synthesis using acetic acid as a catalyst have attempted in situ design of enzyme@COF catalysts. However, these reported strategies inevitably use enzyme-sensitive organic solvents and/or high concentrations of protic acids, greatly reducing their extensibility to different enzymes. Simultaneously, the resulting enzyme@COF catalysts suffer from poor crystallinity, compromising the reticular chemical characteristics and functionality of COFs. To address this, the research team explored the great potential of using green, trace amounts of ILs as catalysts and regulators for preparing highly crystalline enzyme@COF biocatalysts. This work provides a mild, green strategy for designing stable, high-activity biocatalysts and offers new insights for developing multifunctional photo-enzyme catalytic systems¹⁰⁴.

IL/reticular material composites exhibit an exceptionally broad application landscape in heterogeneous catalysis. The core of their catalytic function lies in the deep coupling between the chemical multifunctionality provided by ILs and the confined space offered by reticular materials. The periodic nanopores of reticular materials not only effectively restrict metal species migration and agglomeration during high-temperature reactions or cycling (significantly enhancing cycling stability) but also, through confinement effects such as substrate enrichment and stabilization of transition-state intermediates, synergize with the electronic effects of ILs, often resulting in turnover frequencies and selectivities of composite catalysts far exceeding the simple sum of those of homogeneous ILs or pristine reticular materials.

4. Conclusions and Outlook:

The combination of ionic liquids (ILs) with reticular materials (mainly MOFs and COFs) represents one of the most dynamic research directions at the intersection of porous materials and functional fluids in recent years. The composite is not merely a simple addition of properties but achieves a "rigid-flexible coupling"

through interfacial synergy—"rigid frameworks providing mass transport channels and structural stability, flexible ILs modulating the chemical microenvironment and dynamic response"—demonstrating comprehensive performance superior to either component in strategic areas such as catalysis, separation, and energy storage and conversion.

At the synthetic methodology level, researchers have developed multiple strategies, including ionothermal synthesis, wet impregnation, and post-synthetic chemical modification, expanding the role of ILs from "solvents" to "functional components"¹⁰⁵. In terms of property regulation, ILs can act as "molecular plugs" to precisely narrow the effective pore sizes of reticular materials, thereby enhancing gas separation selectivity; as "structure-directing agents" to modulate the layer stacking modes of 2D COFs (AA → AB switching), thereby affecting their optoelectronic properties; and their introduction can also significantly improve the hydrolysis stability and solution processability of reticular materials, laying the foundation for membrane fabrication and device integration. At the application level, these composites demonstrate significant performance leaps compared to pristine reticular materials or pure ILs in areas such as synergistic CO₂ capture and cycloaddition catalysis, efficient CO₂/N₂ and CO₂/CH₄ membrane separation in natural gas/flue gas, and achieving breakthroughs in ionic conductivity in solid-state electrolytes.

However, as research progresses from "proof-of-concept" to "performance optimization" and even "industrial orientation," several inherent limitations of IL/reticular material composites become apparent for practical applications. The trade-off between IL loading and dispersion uniformity remains challenging to reconcile. Physically loaded composites (IL@MOF/COF) face severe IL leaching during long-term service, while chemically bonded ILCOFs, although solving the leaching issue, often sacrifice the crystallinity and pore regularity of reticular materials due to the introduction of bulky IL moieties, creating a dilemma between "stability" and "order." Furthermore, the vast number of reticular materials (tens of thousands of MOFs and emerging COF topologies) and the immense IL chemical space (theoretically up to 10¹⁸ ion pairs) make the combinatorial "chemical space" nearly infinite. The traditional research paradigm of empirical guidance and case-by-case synthesis is insufficient for efficient exploration, necessitating new methodological interventions¹⁰⁶. Finally, at the mechanistic understanding level, the physicochemical properties of ILs confined in nanopores (e.g., phase transitions, ion dissociation, local viscosity, and diffusion coefficients) differ fundamentally from bulk behavior. However, current in situ/operando characterization techniques for "confined ILs" remain scarce, leaving our understanding of how confinement effects influence catalytic active site microenvironments, mass transfer pathways, and reaction kinetics largely in a "black box" state¹⁰⁷.

Despite these challenges, the unique value of IL/reticular material composite systems remains unwavering, and in fact, the challenges provide clear directions and ample space for further interdisciplinary innovation. The application boundaries of IL/reticular material composites are continuously expanding: in the biomedical field, IL-functionalized MOFs are being explored as enzyme immobilization supports and intelligent drug delivery systems¹⁰⁸. In environmental remediation, these composites have shown significant potential for efficient adsorption of heavy metal ions, radionuclides, and persistent organic pollutants¹⁰⁹. In sensing and detection, the selective recognition capabilities of IL/COF composite membranes for trace gases and volatile organic compounds have also garnered considerable attention¹¹⁰.

The vigorous development of these emerging interdisciplinary directions further enriches the research connotations and application extensions of IL/reticular material composites.

Based on this, the following sections systematically analyze the current research status and evolutionary trends of IL/reticular material composites from two dimensions: "major challenges" and "future development."

4.1 Major Challenges:

Current practical applications of ILs and reticular materials face several key challenges, primarily: (1) "Loading-Pore" Dilemma: There is an inherent conflict between IL loading and the retention of reticular material pore structure. To impart significant functional enhancement to the composite, high IL loading is often required, but high loading inevitably leads to pore blockage, sharp reduction in specific surface area, and pore volume loss¹¹¹. This effect confines the optimal performance of composites to a narrow loading window, the determination of which currently relies heavily on extensive trial-and-error experiments, lacking theoretical prediction tools based on thermodynamic or kinetic models. (2) "Leaching-Crystallinity" Trade-off: Physically loaded composites (IL@MOF/COF) face severe IL leaching under conditions of polar solvents, high flow rates, or high temperatures, leading to performance degradation and shortened material lifespan¹¹². Although covalent bonding fundamentally solves the leaching issue, the significant steric hindrance introduced by bulky IL moieties often interferes with the topological assembly of MOFs/COFs, resulting in reduced crystallinity, decreased specific surface area, and even compromised pore regularity¹¹³. Finding the balance between "structural order" and "functional integration" represents a major obstacle to the widespread adoption of this strategy. Both constitute a dilemma between "stability" and "order." (3) Explosive Growth of "Chemical Space" and Low Screening Efficiency: With over 100,000 reported MOFs and thousands of topological combinations for COFs, and theoretically up to 10¹⁸ ion pairs for ILs, the cross-combination creates a nearly infinite possibility

space. The traditional "synthesis-characterization-testing" trial-and-error model is extremely inefficient, severely constraining the pace of new material discovery. Meanwhile, design guidelines for composites tailored to specific application scenarios have yet to be established; existing structure-property relationships are mostly limited to specific systems and lack general theoretical guidance. This contradiction between the vastness of the "chemical space" and the limitations of current research paradigms has become a structural bottleneck constraining rapid field development.⁽⁴⁾ "Black Box" Mechanistic Understanding and Scale-up Barriers: The molecular behavior of confined ILs (phase transitions, ion dissociation, local viscosity, and diffusion coefficients) differs fundamentally from their bulk state. However, conventional characterization techniques struggle to obtain true information within nanopores. The application of synchrotron XRD, in situ IR/Raman spectroscopy, and solid-state NMR in confined systems faces challenges in spatial and temporal resolution. The core question of "how confinement effects influence catalytic active site microenvironments and reaction kinetics" lacks clear experimental evidence. Simultaneously, the synthesis and purification of high-purity ILs are cumbersome and expensive; large-area defect-free membrane formation of reticular materials faces process stability challenges; and long-term performance data for composites under industrial operating conditions are extremely scarce. These engineering challenges collectively constitute barriers to transitioning from laboratory to practical applications.

4.2 Future Development:

Despite the many challenges currently facing IL/reticular material composites in structural design, interface regulation, and scale-up applications, their research prospects remain highly promising. Future trends will become increasingly diversified, gradually achieving deep integration with advanced material systems, artificial intelligence-assisted design, in situ characterization techniques, and engineering integration, propelling the field from "laboratory proof-of-concept" to "real-world application."

First, novel composite architecture design and function-oriented molecular engineering will be a core direction for IL/reticular material composite development. Compared to the traditional binary modes of physical loading and chemical grafting, a new generation of composites is evolving towards "rigid-flexible coupling" and "intelligent responsiveness." For example, in situ polymerization within reticular material pores to form three-dimensional crosslinked poly(ionic liquid) (PIL) networks¹¹⁴ can fundamentally prevent IL leaching and allow tuning of pore size and local microenvironment via crosslinking density, achieving "high loading" and "preserved pores" simultaneously; developing "core-shell" or "sandwich" multilayer composites spatially integrates catalytic active centers, separation functional layers, and protective layers for ordered multifunctional synergy¹¹⁵. Meanwhile, research

should expand beyond traditional imidazolium/pyridinium ILs to include chiral ILs (for asymmetric catalysis), protic ILs (for high-temperature proton exchange membranes), functionalized anionic ILs (containing amino acid, sulfonate, cyanate groups), and photo/thermo-responsive ILs, endowing composites with dynamically tunable multifunctionality and expanding application spaces in emerging areas such as cascade catalysis, smart responsive separation, and photothermal coupling.

Furthermore, multiscale simulation and artificial intelligence-driven rational design are becoming core drivers for accelerating new material discovery. Facing the vast chemical space arising from cross-combinations of MOFs (>100,000), COFs (thousands of topologies), and ILs (10^{18} ion pairs), the traditional trial-and-error approach is insufficient. Establishing a multiscale computational framework—"Density Functional Theory (DFT)-Molecular Dynamics (MD)-Finite Element Macroscopic Simulation"—systematically reveals the structural evolution, ion dissociation behavior, and diffusion dynamics of confined ILs at the molecular level, enabling high-throughput virtual screening and inverse design. Such approaches are expected to significantly enhance the efficiency of new material discovery, accelerating the transition from "empirical-guided experimentation" to "data-driven design."

In terms of technological breakthroughs, the combination of multiple advanced characterization techniques is gradually transforming the "black box" of confined ILs into a "transparent box." Developing in situ liquid-phase transmission electron microscopy (In situ Liquid TEM) to observe the filling, migration, and aggregation behavior of ILs within pores in real time¹¹⁶. Chen and co-workers, through systematic spectroscopic, structural, and electrochemical characterization, revealed that BMImHSO₄@MOF-808 composites effectively optimize the Pt/ionomer interface structure and processes: the unsaturated Zr sites of MOF-808 can coordinate with sulfonate groups of PFSA, significantly inhibiting their adsorption on Pt surfaces and releasing more catalytic active sites; the hydrophobic nature of BMImHSO₄ and the ordered pores of MOF-808 synergistically construct efficient oxygen diffusion channels¹¹⁷; meanwhile, BMImHSO₄ enhances proton conductivity and improves humidity adaptability¹¹⁸. This provides direct experimental evidence for understanding confinement catalysis mechanisms. Multi-technique spatiotemporal resolution coupling is expected to establish a full-chain structure-property relationship of "confined structure-molecular dynamics-macroscopic performance," providing a solid experimental foundation for rational material design¹¹⁹.

In summary, IL/reticular material composites are evolving from the simple "functional additive-porous support" composite mode to an integrated intelligent material platform with designable structures, programmable functionalities, and tunable responsiveness¹²⁰. In the future, through continuous

innovation in synthetic methodology¹²¹, multiscale simulation and AI-driven rational design, breakthroughs in situ characterization techniques, and the synergistic advancement of engineering integration and device fabrication¹²², IL/reticular material composites are expected to achieve a leap from fundamental research to practical applications in strategic areas such as energy conversion, environmental remediation, biocatalysis, and intelligent sensing.

Data availability

Not applicable.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

Y. Z. P. and Y. X. S.: Literature search, writing of the manuscript. Z. X.: Manuscript review and editing, literature curation, article optimization, data curation, project administration. W.-H. L.: Manuscript review and editing, project administration, and funding acquisition. All the authors have approved the final manuscript.

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