

Porous Nanomaterials for Iodine Adsorption

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Abstract

As global environmental issues become increasingly severe, the overconsumption of traditional energy sources and the associated pollution problems have become more prominent, creating an urgent need to find cleaner and more efficient alternative energy sources. In this context, nuclear energy, as a low-carbon and high-efficiency energy option, has gradually gained widespread attention. With the continuous development of nuclear technology, the application of nuclear energy has expanded globally. However, the widespread use of nuclear energy has also brought about various environmental challenges, particularly in terms of nuclear waste disposal, radiation safety, and the risk of nuclear accidents, which have sparked extensive discussions on the sustainability of nuclear energy. Of particular concern is the radioactive iodine released during uranium fission reactions, which poses significant potential risks to human health and the ecological environment, making the removal and enrichment of iodine an urgent issue. To address this challenge, porous nanomaterials, with their excellent adsorption properties and high surface area, have become a research hotspot in recent years and shown great potential for iodine removal and enrichment. This review focuses on the application of porous nanomaterials in iodine adsorption, including metal-organic frameworks (MOFs), covalent organic frameworks (COFs), and porous organic polymers (POPs), and discusses the synthesis methods of these materials as well as their practical applications in iodine removal. Finally, the future development trends of porous nanomaterials in iodine adsorption are also envisioned.

Keywords

MOFs; COFs; POPs; Iodine.

1. Introduction

As global energy demand continues to rise and environmental issues become increasingly severe, the overconsumption of traditional energy sources and the associated pollution have become focal points of worldwide concern.[1, 2] Carbon emissions from energy production and consumption are accelerating climate change, while also raising widespread concerns about environmental health and ecological safety. Against this backdrop, nuclear energy, as a low-carbon and highly efficient alternative energy source, has gradually garnered attention from governments and research institutions around the world. The key advantage of nuclear energy lies in its ability to provide large amounts of energy with relatively low carbon emissions. However, its widespread use also brings numerous challenges that need to be addressed, particularly in terms of nuclear waste disposal, radiation safety, and the risks of nuclear accidents. [3, 4] These issues pose threats not only to human health but also to the long-term stability of the ecological environment. [5]

The radioactive substances released during nuclear fission reactions, especially radioactive iodine, are a critical concern due to their persistence in the environment and potential harm to

human health. The removal and enrichment of iodine has thus become one of the key issues for the sustainable development of nuclear energy. The accumulation and release of radioactive iodine not only pose direct threats to the ecosystems and populations surrounding nuclear power plants but also risk causing irreversible ecological damage due to its long-term persistence in the environment. [6, 7] Therefore, the development of effective iodine removal technologies, particularly materials capable of efficiently adsorbing and enriching radioactive iodine, has become an important research direction in the nuclear energy field.

In recent years, with the rapid development of materials science and nanotechnology, porous nanomaterials have emerged as ideal candidates for iodine removal and enrichment due to their high surface area, excellent adsorption properties, and good selectivity. Porous nanomaterials such as metal-organic frameworks (MOFs)[8, 9], covalent organic frameworks (COFs) [10, 11], and porous organic polymers (POPs) [12, 13] have demonstrated significant potential in iodine adsorption, owing to their highly tunable pore structures and functionalized surfaces. These materials not only efficiently capture radioactive iodine but also exhibit high stability and regenerability under various conditions, offering feasible solutions for nuclear waste treatment.

This review aims to summarize the progress in the application of porous nanomaterials for iodine adsorption, discussing the synthesis methods, performance characteristics, and practical applications of materials such as MOFs, COFs, and POPs in iodine removal and enrichment. Additionally, the review will explore the future development trends of iodine adsorption technologies using porous nanomaterials in the nuclear energy sector, emphasizing their significant potential for enhancing the safety and sustainability of nuclear energy.

2. Nanomaterials for Iodine Adsorption

2.1. Metal-organic Framework Materials (MOFs)

As shown in Fig.1, Wang et al. [14] successfully synthesized PVP-modified amino-functionalized composite MOF-on-MOF adsorbents through epitaxial growth. Characterization confirmed the successful preparation of $\text{NH}_2\text{-MIL-101-on-NH}_2\text{-UiO-66}$, which exhibited thermal stability up to 360°C . Adsorption experiments showed that $\text{NH}_2\text{-MIL-101-on-NH}_2\text{-UiO-66}$ exhibited remarkable iodine adsorption capacity, with a capture ability of 1930 mg/g , reaching equilibrium within 4 hours. Furthermore, $\text{NH}_2\text{-MIL-101-on-NH}_2\text{-UiO-66}$ retained effective iodine capture ability after six cycles of iodine adsorption-desorption, demonstrating stable structural integrity. DFT calculations revealed that the active sites, Zr-oxo/Al-oxo clusters, and amino groups enhanced iodine affinity through $\text{Zr-oxo}\cdots\text{I}$, $\text{C=O}\cdots\text{I}$, and $\text{N-H}\cdots\text{I}$ interactions. Xia et al. [15] synthesized MOF-5 through hydrothermal synthesis, which exhibited an irregular shape with most parts being block-like. MOF-5 possessed large surface area, pore volume, and thermal stability. Adsorption experiments at 75°C for volatile iodine demonstrated that MOF-5 had a high capture capacity, with a maximum adsorption capacity of 0.63 g/g . Kinetic fitting indicated that the process was mainly governed by chemical adsorption. After six cycles of adsorption and desorption, MOF-5 retained good adsorption performance and stability. In the liquid phase, the iodine capture capacity of MOF-5 was 155 mg/g , which differed from its gas-phase iodine adsorption. Molecular simulations indicated that the non-metallic O atoms and Zn metal atoms in MOF-5 were more involved in interactions with I_2 .

Studies have shown that electron-rich groups containing heteroatoms exhibit strong affinity for iodine. Mandal et al. [16] successfully synthesized a three-dimensional metal-organic framework (MOF) with the chemical formula $[\text{Mn}_2(\text{oxdz})_2(\text{tpbn})(\text{H}_2\text{O})_2]\cdot 2\text{C}_2\text{H}_5\text{OH}_n$, utilizing a multi-site bis(tridentate) ligand. This MOF material features an 8-fold interpenetrated 3D framework with abundant nitrogen-containing sites. At 70°C , the equilibrium uptake of iodine vapor was $2.13 \pm 0.05\text{ g/g}$, with each framework unit encapsulating four iodine molecules. In

addition to vapor adsorption, iodine removal efficiency from cyclohexane solution (200 ppm) was 68%, with a corresponding maximum absorption value of 168 mg/g. The iodine uptake capacity in saturated KI aqueous solution was determined to be 1.1 ± 0.05 g/g.

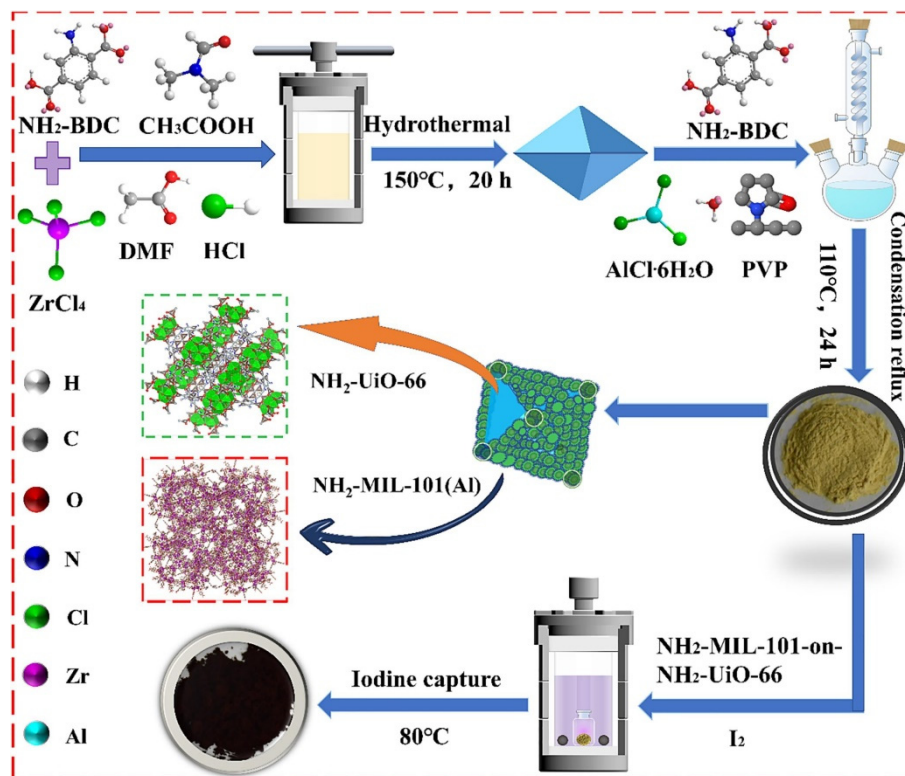


Figure 1. Preparation of $\text{NH}_2\text{-MIL-101-on-NH}_2\text{-UiO-66}$ and its mechanism of iodine vapor trapping. [14]

Moreover, synthesizing MOF@COF composite structures is another common method for enhancing iodine adsorption. Wang et al. [17] first synthesized $\text{NH}_2\text{-MOF}$ via solvothermal synthesis and then covalently modified it using a solution suspension method. $\text{NH}_2\text{-MOF}$ contains a large number of amino groups, while $\text{COF@NH}_2\text{-MOF}$ exhibits numerous -C=N- structures, which can provide abundant electrons and interact with iodine receptors. Adsorption isotherm models indicated that after covalent modification, the iodine adsorption capacity of $\text{NH}_2\text{-MOF}$ increased from 949.52 mg/g to 2157.44 mg/g. Kinetic models suggested that iodine adsorption primarily occurred via chemical adsorption. Mechanistic studies revealed weak interactions between the benzene rings of $\text{NH}_2\text{-MOF}$ and iodine, with electron-rich amino groups donating electrons to iodine, thus enhancing adsorption. The imine bonds in $\text{COF@NH}_2\text{-MOF}$ provide electron transfer and interact with I_3^- , I^- , and I_2 in water. The presence of a large number of imine bonds plays a crucial role in enhancing iodine adsorption. This material exhibits high iodine selectivity and can operate under high-pressure environments.

Increasing porosity is also an effective way to improve iodine adsorption. Forgan et al. [18] extended the construction of a series of Zr-based MOF materials in the form of UiO-66, with unsaturated olefin and alkyne units serving as linkers. Nenoff et al. [18] presented a comprehensive structural and modeling analysis, describing the preferential adsorption of molecular iodine into Cu-BTC from an I_2 and water vapor mixed gas stream. Molecular dynamics (MD) simulations revealed that I_2 molecules had stronger binding in smaller cages and lower mobility than in larger pore systems. I_2 molecules preferentially localized near Cu wheels and benzene-tricarboxylate linkers, forming a hydrophobic barrier that suppressed

water vapor adsorption within the hydrophilic Cu-BTC pores, achieving an exceptionally high I/Cu ratio of 3.5.

Additionally, loading MOF materials onto the surface of other materials is another current effective method to enhance iodine adsorption performance. Zhu et al. [19] reported a stable and recyclable electrospun fiber adsorbent containing various binding sites, including nitrogen-functional groups (cationic quaternary ammonium and neutral amines) and porous materials (UIO-66-NH₂). The adsorbent was prepared by combining electrospinning with subsequent functionalization. Due to the synergistic effect of the constructed binding sites, the material efficiently adsorbed iodine from aqueous media (with an adsorption capacity as high as 3.5 g/g) and exhibited fast adsorption kinetics (I₂ aqueous solutions reached equilibrium within 180 minutes, and I₃⁻ aqueous solutions within 240 minutes). Additionally, the fiber adsorbent demonstrated excellent selectivity even in real water samples, along with good recyclability.

2.2. Covalent Organic Framework Materials (COFs)

Covalent Organic Frameworks (COFs) are a class of highly ordered, porous materials formed by the covalent bonding of organic units. Unlike Metal-Organic Frameworks (MOFs), COFs are entirely composed of organic molecules, typically exhibiting superior chemical stability and a lighter structure. The key feature of COFs lies in their highly tunable structure, which allows for the design and synthesis of materials with specific pore structures and functionalities by selecting different organic monomers and reaction conditions. Due to their molecular-level order and high surface area, COFs have shown promising applications in various fields such as gas storage, catalysis, drug delivery, sensing, and adsorption.

The advantages of COFs materials lie in their exceptional stability, particularly under extreme environmental conditions (e.g., strong acids, strong bases, or high temperatures), which make them particularly suitable for applications under such conditions. Since COFs are entirely composed of organic molecules, they not only avoid the corrosion issues associated with metal centers but also allow for precise structural design of the organic framework, enabling control over the pore size, surface functional groups, and molecular interactions. In the removal and enrichment of radioactive iodine, COFs enhance their selectivity and adsorption capacity for target molecules through both physical and chemical adsorption, facilitated by their tunable pore structure and abundant organic functional groups.

Furthermore, the synthesis methods for COFs typically involve simple, repeatable chemical reactions, such as amidation, polycondensation, and covalent bonding. These methods are not only straightforward but also highly scalable, making COFs materials promising for industrial-scale production and large-scale applications. Overall, COFs, with their excellent stability, tunability, and wide-ranging functionalization capabilities, have become a key component in the field of novel porous materials and demonstrate vast application potential in environmental protection, energy storage, catalysis, and biomedical fields.

2.2.1. Iodine Adsorption by Heteroatom-containing COFs

As shown in Fig.2, the team of Ma Lijian [20] from Sichuan University synthesized CTP-6-CHO by modifying hexachlorocyclotriphosphazene, and used CTP-6-CHO as the reaction center to synthesize a series of quasi-three-dimensional (Q-3D) Covalent Organic Framework (COF) materials via a Schiff base reaction. The synthesized QTD-COF features unique slanted triangular front-side pores and large interlayer distances (0.41–0.45 nm), presenting a leaf-like Q-3D structure. This successfully constructs three-dimensional structural features on a two-dimensional material, significantly enhancing the permeability and mass transfer rate of 2D COFs. The unique pore structure of the COF allows guest molecules to enter the material's framework through side-pathways, thereby enhancing the interaction between host and guest molecules in a more orderly and efficient manner. Adsorption experiments demonstrated that

QTD-COF exhibits significantly superior iodine adsorption rates and outstanding adsorption capacity compared to traditional 2D COFs. In particular, for QTD-COF-V, the adsorption rate constant (K80%) reached $2.51 \text{ g}\cdot\text{h}^{-1}$, with an adsorption capacity of $6.29 \text{ g}\cdot\text{g}^{-1}$, showing excellent material reusability and irradiation stability. Comparative studies revealed that the lateral pore size, interlayer distance, and iodine adsorption rate of QTD-COF increased with the length and flexibility of the linking monomers, indicating that by controlling the monomer chain length and flexibility, successful modulation of COF's adaptability to guest molecules and adsorption performance was achieved.

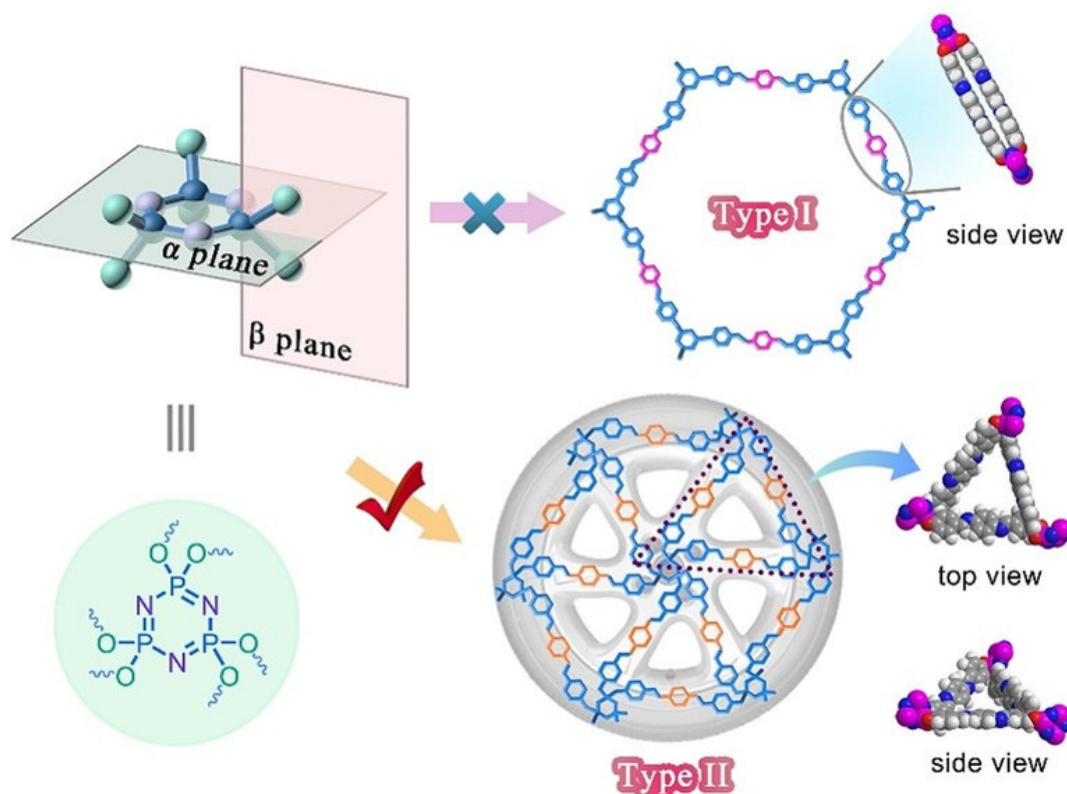


Figure 2. Synthesis of Q-3D COF and iodine adsorption [20]

Li et al. [21] designed five imine-functionalized COFs using triazine-based aldehyde, 2,4,6-tri(4-formylphenoxy)-1,3,5-triazine (TPT-CHO), and biphenylamine (BD) derivatives. The saturated adsorption capacities ($X = 0, 25, 50, 75, 100$) of TPT-DHBDx COF were approximately 5.43, 4.65, 4.30, 4.12, and 3.88 g/g, respectively. All the products exhibited relatively high adsorption capacities, especially TPT-BD COF, which showed iodine absorption rates higher than all previously reported solid adsorbents. Hydrogen bonding interactions "lock" some COF structures, reducing the rotational freedom of flexible units and increasing the flatness of the 2D layers, thereby significantly enhancing the microstructural order and crystallinity of COFs. Due to their high nitrogen content and rich electron-rich π -conjugated systems, TPT-DHBDx COF exhibited highly efficient, reversible, and ultrahigh iodine adsorption capacity, with a maximum capacity of up to 543 wt%, which is unprecedented. Furthermore, the synthesized COF demonstrated good irradiation stability and could withstand γ -ray exposure of 105 Gy, indicating its potential for capturing radioactive iodine (such as ^{129}I or ^{131}I) under specific conditions. Mechanistic studies further revealed that hydrogen bonding interactions occupy some of the active adsorption sites and inhibit iodine from approaching the imine linkage via a spatial blocking effect, which provides valuable guidance for the design and fabrication of iodine capture materials.

Zou et al. [22] designed a triphenylamine derivative as the main chain of the COF backbone and successfully synthesized three novel electron-rich COFs for capturing both gas-phase and liquid-phase iodine. The maximum adsorption capacity of TAPD-MPD was $5.10 \text{ g}\cdot\text{g}^{-1}$ (75°C) and $3.31 \text{ g}\cdot\text{g}^{-1}$ (25°C). When no heteroatoms were present in the side chains, the maximum adsorption capacities of TAPD-PDB and TAPD-TDB increased to $7.88 \text{ g}\cdot\text{g}^{-1}$ and $6.85 \text{ g}\cdot\text{g}^{-1}$ (75°C), and $4.46 \text{ g}\cdot\text{g}^{-1}$ and $3.62 \text{ g}\cdot\text{g}^{-1}$ (25°C), respectively. Moreover, the adsorption rate constant ($K_{80\%}$) significantly increased from $1.54 \text{ g}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$ to $5.34 \text{ g}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$ and $4.22 \text{ g}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$. These three COFs exhibited excellent chemical stability, thermal stability, radiation stability, and reusability. The ultra-fast and ultra-high iodine adsorption capacity can be attributed to the COFs' rich electronic structure, effective adsorption sites, helical conformation, and charge transfer interactions.

2.2.2. Iodine Adsorption by Nitrogen-rich COFs

Nitrogen-rich structures and electron-rich π -conjugated systems (such as aromatic rings) can provide effective binding sites for iodine adsorption. In particular, the presence of nitrogen atoms significantly enhances the material's iodine adsorption capacity. Li et al. [23] successfully synthesized two covalent organic frameworks (COFs), TFBT-1 and TFBT-2, through a condensation reaction involving acylamide organic units and two tridentate amine-modified Schiff base polymer modules. Structural analysis revealed that both COFs are nanoporous materials with one-dimensional channels derived from the stacking of their respective 2D frameworks. The iodine adsorption capacities of TFBT-1 and TFBT-2 increased almost linearly in the initial stages, reaching 50% of their saturation capacity within just 5 hours. A distinct inflection point occurred around 20 hours, indicating that adsorption equilibrium was nearly achieved. The maximum iodine uptake was calculated to be 3.15 g/g for TFBT-1 and 2.60 g/g for TFBT-2, based on adsorption values obtained after 50 hours. After three iodine adsorption cycles, the recovered samples still exhibited impressive iodine adsorption capacities of 2.0 g/g for TFBT-1 and 1.66 g/g for TFBT-2. The decrease in adsorption capacity was likely due to the occupation of some active sites by chemically adsorbed iodine species.

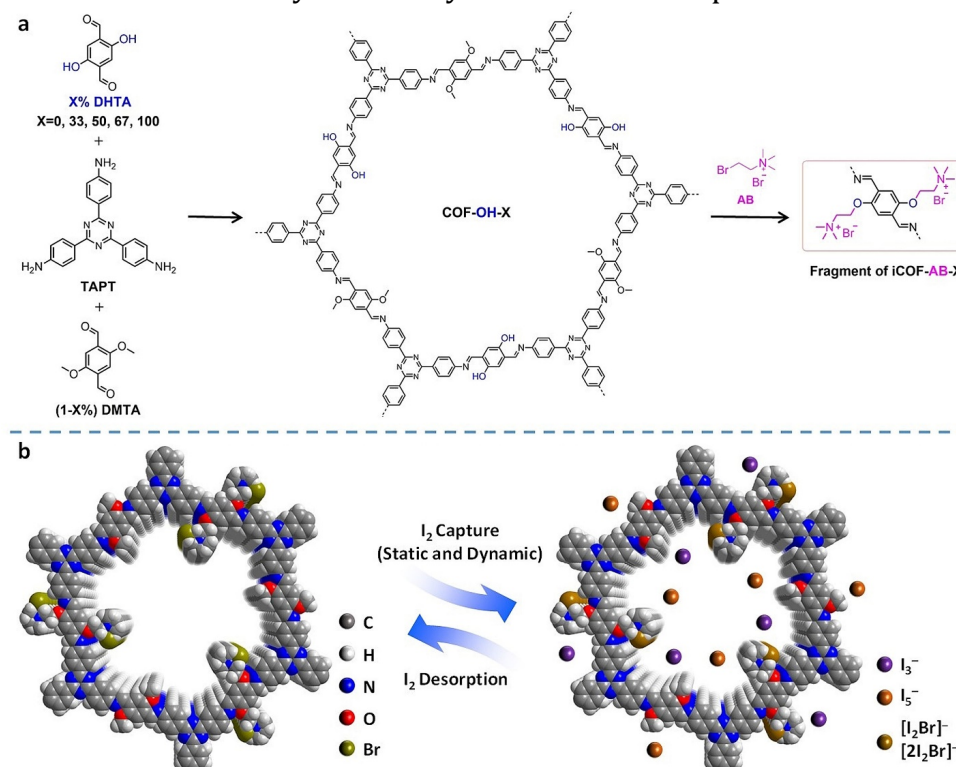


Figure 3. (a) Synthesis process of COF-OH-X. (b) Synthesis process of iodine adsorption of COF-OH-X.[24]

To enhance the host-guest interaction between the COF framework and iodine, Wang et al. [25] selected 2,2'-bipyridine-5,5'-dicarbaldehyde (2,2'-BPy-DCA) as a functional ligand and designed and synthesized a robust nitrogen-rich COF (SCU-COF-2). SCU-COF-2 set at least two new records: a static iodine uptake of 1.45 g/g for CH₃I and a dynamic iodine uptake of 0.98 g/g for I₂. More importantly, these capacities were not significantly affected by the hydrophobicity of the channels in SCU-COF-2, making it particularly attractive for practical applications, such as spent nuclear fuel remediation or emergency iodine or organic iodine leakage during nuclear accidents.

Zhao et al. [26] designed and synthesized four cage-based COFs, namely Cage-TFB-COF, Cage-NTBA-COF, Cage-TFPB-COF, and Cage-TFPT-COF, by using nitrogen-rich organic cages as core modules and four tridentate organic components as linkers through Schiff base polycondensation reactions. Adsorption experiments revealed that all the synthesized COFs exhibited significantly enhanced iodine adsorption capacities. Notably, Cage-NTBA-COF demonstrated an iodine adsorption capacity of 304 wt%, which was 14 times higher than that of the solid cage sample itself. Furthermore, it showed excellent reusability after desorption.

2.2.3. Other COFs for Iodine Adsorption

As shown in Fig.3, Han [24] designed and synthesized a series of ionically functionalized covalent organic frameworks (iCOFs) for iodine capture using a multivariate strategy combined with post-synthesis modification. The initial COF was constructed from a mixture of 2,4,6-tris(4-aminophenyl)-1,3,5-triazine (TAPT) and 2,5-dimethoxyterephthalaldehyde (DMTA) and 2,5-dihydroxyterephthalaldehyde (DHTA). The condensation between primary amines and aldehydes formed an extended framework via imine bonds. The COF was then modified with (2-bromoethyl)trimethylammonium (AB), yielding the ionically modified iCOFs, iCOF-AB-X. Although the modified ion-based COFs exhibited lower surface areas and pore volumes, they demonstrated significantly higher iodine adsorption capacities. For example, iCOF-AB-50 had a lower pore volume of 1.21 cm³·g⁻¹, which is two-thirds that of COF-OH-50, yet it displayed a higher iodine adsorption capacity of 10.21 g·g⁻¹. Moreover, the iodine adsorption behavior was further studied through fixed-bed column breakthrough experiments with a 400 ppm iodine concentration at both 25°C and 75°C. The COF-OH-50 was able to detect iodine after 9 hours at 25°C and 1.5 hours at 75°C, while iCOF-AB-50 extended the detection time to 50 hours at 25°C and 7 hours at 75°C. In terms of reusability, the COF was soaked in ethanol and dried at 100°C. The dynamic adsorption capacity of iCOF-AB-50 was maintained after three cycles. The improved iodine absorption capacity and kinetic performance of iCOF-AB-50 can be attributed to the presence of bromide ions as part of the ionic functional group.

2.3. Porous Organic Polymers (POPs)

Porous Organic Polymers (POPs) are a class of porous materials formed by covalently bonded organic units, characterized by high structural tunability and excellent chemical stability. Compared to Metal-Organic Frameworks (MOFs) and Covalent Organic Frameworks (COFs), POPs stand out because they are entirely composed of organic molecules and do not contain metal centers. This gives POPs unique advantages in certain specialized applications, particularly in terms of corrosion resistance, chemical stability, and biocompatibility. POPs not only possess a large specific surface area and high porosity but also allow for the regulation of their adsorption, catalysis, and separation functions through careful design of their molecular structures and pore sizes.

The synthesis methods of POPs are diverse, including traditional polymerization reactions (such as addition polymerization, condensation reactions, etc.) as well as modern controlled polymerization techniques (such as free radical polymerization, template synthesis, etc.). These methods enable precise design and control at the molecular level, yielding materials with different pore sizes, functionalized surfaces, and diverse physicochemical properties. Due to

their tunable structures, POPs have shown great potential in various applications, including gas adsorption, catalysis, sensing, drug delivery, and pollutant removal.

In particular, for the removal of radioactive substances, POPs materials, with their rich porous structures and tunable functionalized surfaces, can effectively adsorb and concentrate various harmful molecules. For example, in the removal of radioactive iodine, POPs can preferentially select and capture iodine molecules through their unique pore structures and chemical adsorption capabilities, demonstrating high adsorption performance and good stability. Furthermore, because POPs are typically synthesized from relatively simple organic monomers, their synthesis process is not only cost-effective but also feasible for large-scale production.

POPs can be classified based on bonding types, crystallinity, and pore structure, including intrinsic microporous polymers, conjugated microporous polymers, supercross-linked polymers, and covalent triazine frameworks.

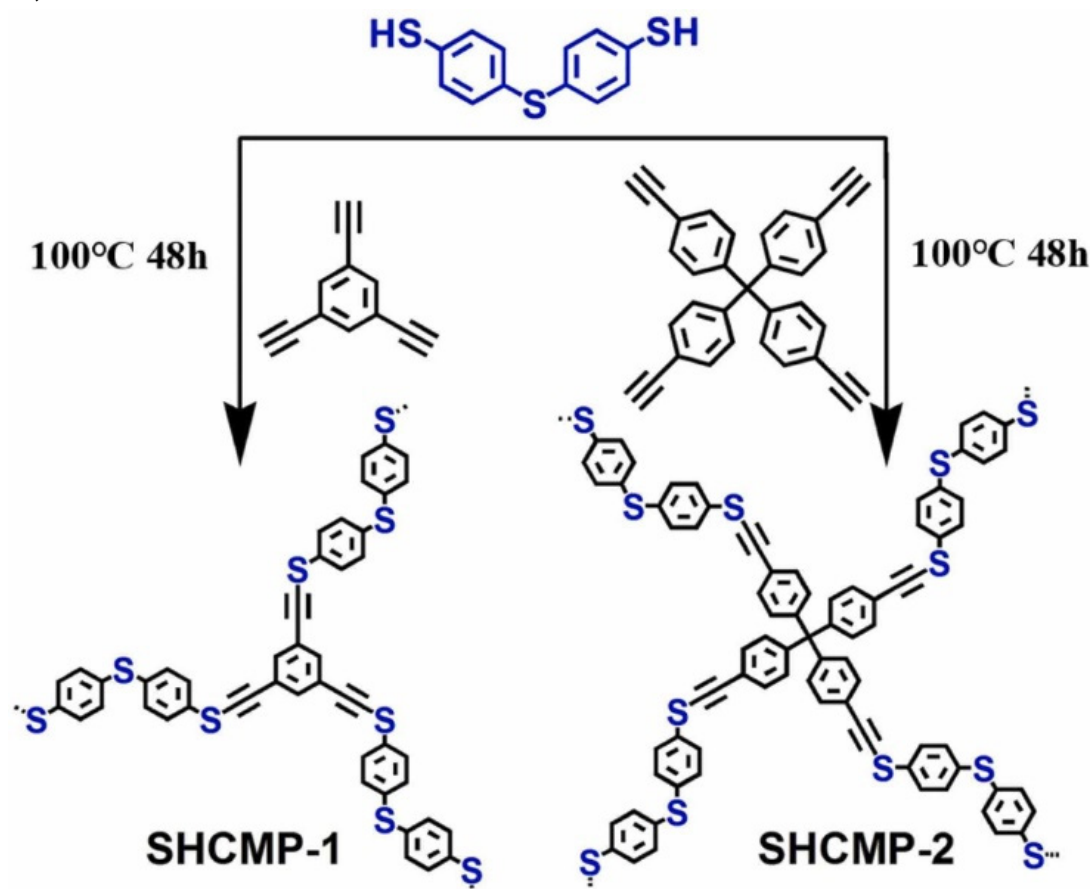


Figure 4. Schematic diagram of the synthesis of the polymers SHCMP-1 and SHCMP-2. [27]

In 2002, Budd and McKeown [28, 29] introduced the concept of intrinsic microporous polymers (PIMs). PIMs are a class of polymer materials that spontaneously form microporous structures, typically with pore sizes between 1 to 2 nanometers. The pores naturally exist within the chemical structure, without the need for external templates or post-treatment. These materials have shown extensive application potential in gas storage, separation, catalysis, and environmental protection. Due to their unique porous structures, high specific surface areas, and excellent gas adsorption and separation properties, PIMs have also attracted widespread attention in iodine adsorption.

Lin et al. [30] synthesized high-molecular-weight PIM-1 powder via the base-catalyzed condensation polymerization of TTSBI and TFTPN at high temperatures. The material not only achieved an exceptionally high iodine vapor adsorption capacity of $860 \text{ mg}\cdot\text{g}^{-1}$, but also successfully indicated the presence of iodine by monitoring fluorescence intensity. The

response was rapid, taking only a few seconds, and the quenching efficiency reached 99.99%, with a detection limit of $1.24 \times 10^{-9} \text{ mol} \cdot \text{L}^{-1}$. Liang et al. [31] developed three nitrogen-rich conjugated microporous polymers (CMP-LS4-6) through Pd-catalyzed Sonogashira and Suzuki cross-coupling reactions. Based on nitrogen desorption experiments, CMP-LS5 exhibited an ultra-high specific surface area of $1185 \text{ m}^2 \cdot \text{g}^{-1}$. The three materials showed high adsorption capacities of $3.32 \text{ g} \cdot \text{g}^{-1}$, $4.40 \text{ g} \cdot \text{g}^{-1}$, and $2.44 \text{ g} \cdot \text{g}^{-1}$, respectively, and the synthesized CMP adsorbents were easy to recycle, offering valuable guidance for designing novel electron-rich CMPs as efficient iodine adsorbents for addressing iodine pollution.

Conjugated Microporous Polymers (CMPs) are composed of conjugated organic units linked by covalent bonds, with highly ordered porous structures, excellent electronic conductivity, and stable physicochemical properties. Due to the excellent performance of CMPs, numerous reactions have been applied in their synthesis, including Schiff base reactions [32], Sonogashira-Hagihara [33] cross-coupling reactions, and Yamamoto coupling reactions [34].

As shown in Fig.4, Xu et al. [27] synthesized SHCMP-1 and SHCMP-2 using 4,4'-dimercaptodiphenyl sulfide (DMDPS) as the core unit, with 1,3,5-triacetylene benzene and tetra(4-ethynylphenyl)methane (TEPM) as comonomers. They exhibited good iodine capture abilities, with saturated iodine adsorption capacities of 590 and 495 wt%, respectively.

Supercross-linked polymers are a class of materials that enhance their network structures through chemical cross-linking, offering higher thermal stability, chemical stability, and mechanical strength. [35] Zhao et al. [36] synthesized a series of highly cross-linked polymers based on phenylhydrazine for gas-phase and aqueous-phase iodine adsorption. The obtained polymers exhibited good thermal stability and high surface areas. Among them, Z-HCP-1 demonstrated an impressive iodine vapor adsorption capacity of $6.49 \text{ g} \cdot \text{g}^{-1}$, while its iodine removal efficiency in aqueous solutions reached 96.1%, maintaining over 90% in complex water environments containing interfering ions. This high performance is primarily attributed to the presence of phenyl rings and primary amine groups in Z-HCP, which exhibit excellent iodine adsorption performance through synergistic interactions and monolayer chemical adsorption. Furthermore, Z-HCP showed remarkable cyclic stability, emphasizing its practical applicability.

Covalent Triazine Frameworks (CTFs) possess a stable structure, good chemical resistance, and high porosity, giving them significant advantages in adsorption and separation fields. Xu et al. [37] successfully synthesized six novel CTFs containing triazine rings using Lewis acid ZnCl_2 as a catalyst at different reaction temperatures. Compared to the FCTF@350, NCTF@350, and ClCTF@350 polymers prepared at 350°C , the polymers FCTF@400, NCTF@400, and ClCTF@400, synthesized at 400°C , exhibited higher specific surface areas, larger pore volumes, and more uniform pore size distributions. These polymers displayed high iodine adsorption performance, with iodine capture amounts of 285, 232, 231, 382, 372, and 340 wt% for FCTF@350, NCTF@350, ClCTF@350, FCTF@400, NCTF@400, and ClCTF@400, respectively. The results indicate that the introduction of electron-rich F and pyridine N groups enriched the adsorption sites of CTFs, enhancing the interactions between the adsorbent and iodine molecules, leading to higher iodine adsorption capacities for FCTFs and NCTFs.

3. Iodine Adsorption Comparison of MOFs, COFs, and POPs

In the field of iodine adsorption, porous materials such as Porous Organic Polymers (POPs), Metal-Organic Frameworks (MOFs), and Covalent Organic Frameworks (COFs) each demonstrate unique advantages and application potential. Although they are all highly tunable porous materials with large specific surface areas, their performances in iodine adsorption differ due to their distinct structural characteristics and compositions.

Firstly, MOFs, owing to the incorporation of metal ions or metal clusters, provide additional coordination and electrostatic interactions, which often lead to stronger selectivity and higher adsorption capacities in iodine capture. The pore structure of MOFs can be precisely tuned by selecting metal centers and designing organic ligands, optimizing their adsorption performance for radioactive iodine. Moreover, MOFs exhibit good stability and high regeneration capabilities, which are crucial for repeated use in practical applications. However, the stability of MOFs may be compromised in extreme conditions, particularly in strong acidic or basic environments, due to the potential influence of the metal centers.

In contrast, COFs are entirely composed of organic units without any metal centers, which gives them superior chemical stability, especially under extreme conditions such as strong acids or high temperatures. The structure of COFs is covalently bonded, imparting high thermal stability and corrosion resistance. In iodine adsorption, COFs also demonstrate good performance, especially when organic monomers with specific functional groups are designed to enhance interactions with iodine molecules. The main advantage of COFs lies in their ability to precisely control pore size and surface functionalization by tuning the type and arrangement of organic units, thus optimizing adsorption performance. However, due to the absence of metal centers, COFs may exhibit lower adsorption capacities and selectivity compared to MOFs in certain cases.

POPs, as entirely organic porous materials, offer high structural flexibility and excellent chemical stability. They are typically synthesized through simple organic reactions, which make them cost-effective and scalable. In iodine adsorption, POPs can efficiently capture radioactive iodine due to their tunable pore sizes, abundant functional groups, and good physical adsorption capabilities. The primary advantages of POPs are their simple synthesis process and good environmental adaptability, particularly for long-term use in complex environments. However, POPs may be slightly less effective in terms of adsorption capacity and selectivity, particularly when compared to MOFs and COFs, mainly due to their relatively less-developed pore structures and lower degree of functionalization.

In summary, MOFs, COFs, and POPs each have their distinct characteristics in iodine adsorption applications. MOFs have the advantage of metal centers, offering superior adsorption capacity and selectivity. COFs, with their excellent chemical stability and resistance to high temperatures, perform better under extreme conditions. POPs, on the other hand, are cost-effective, easily synthesized, and well-suited for long-term use in complex environments, making them highly competitive in practical applications. Depending on the specific application requirements, these three materials can be reasonably selected and may complement each other in iodine removal and enrichment technologies.

4. Conclusion and Outlook

In the field of iodine adsorption, Metal-Organic Frameworks (MOFs), Covalent Organic Frameworks (COFs), and Polymeric Organic Frameworks (POPs) have demonstrated significant potential for practical applications. MOFs, with their highly tunable porosity and abundant metal sites, exhibit superior iodine adsorption performance, particularly in terms of high efficiency in capturing iodine. COFs, due to their well-ordered structures and excellent chemical stability, offer high selectivity and adsorption capacity, making them suitable for iodine capture in complex environments. POPs, with their tunable chemical properties and structural flexibility, also show promise for iodine adsorption, especially in large-scale industrial applications where stability and recyclability are crucial.

However, despite the advancements in iodine adsorption, several challenges remain. First, the synthesis methods and scalability of MOF and COF materials need further optimization to reduce costs and enhance their practical feasibility. Moreover, the long-term stability and

recyclability of these materials in real-world applications are not yet fully established, necessitating improvements in their design and functionalization. While POPs exhibit potential in iodine capture, there is room for improvement in their selective adsorption capabilities and overall efficiency. Future research could focus on multi-scale structural design and functional optimization to enhance the adsorption performance, stability, and recyclability of these materials.

Looking ahead, as synthesis techniques and characterization methods continue to advance, MOFs, COFs, and POPs are poised to find even broader applications in iodine adsorption. In particular, the integration of artificial intelligence and high-throughput screening technologies will accelerate the discovery of novel, high-performance adsorbents, providing more reliable and sustainable solutions for environmental remediation and energy applications.

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