

A REVIEW ON THE SYNTHESIS STRATEGIES AND FACTORS CONTRIBUTING TO THE FORMATION OF ZEOLITIC IMIDAZOLATE FRAMEWORKS (ZIFs) AND THEIR APPLICATIONS

(Ulasan Strategi Sintesis dan Faktor yang Menyumbang Pembentukan Kerangka Zeolit
Imidazolat (ZIFs) dan Aplikasi)

Nazhirah Muhammad Nasri^{1,2}, Enis Nadia Md Yusof³, Velan Raman^{1,2}, Abdul Halim Abdullah^{1,4},
and Mohamed Ibrahim Mohamed Tahir^{1,2*}

¹Department of Chemistry, Faculty of Science, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan,
Malaysia

²Foundry of Reticular Materials for Sustainability (FORMS), Institute of Nanoscience and Nanotechnology (ION2), Universiti
Putra Malaysia, Serdang 43400, Selangor, Malaysia

³Chemical Sciences Programme, School of Distance Education, Universiti Sains Malaysia, Minden, Penang 11800, Malaysia

⁴Institute of Nanoscience and Nanotechnology (ION2), Universiti Putra Malaysia, Serdang 43400, Selangor, Malaysia

*Corresponding author: ibra@upm.edu.my

Received: 6 November 2023; Accepted: 5 January 2024; Published: 28 February 2024

Abstract

Zeolitic Imidazolate Frameworks (ZIFs) are a subclass of Metal-Organic Frameworks (MOFs) that have attracted significant attention due to their unique properties such as high surface area, tunable pore size, and excellent thermal and chemical stability. The review aims to discuss reported single and mixed-linker of ZIFs. The synthesis of ZIFs can be achieved through various methods such as solvothermal, hydrothermal, ionothermal, microwave-assisted, sonochemical, contra-diffusion synthesis, and mechanochemical. The review discusses the benefits and disadvantages of each method as well as a critical analysis of their effectiveness. The synthesis factors of ZIFs are classified into several types such as organic solvents, additives, concentration, temperatures, metal salt variations and the reaction time. Furthermore, the paper highlights several applications of ZIFs, including their impact on adsorption of pollutants, catalysis and drug delivery system. The paper concludes by summarising the recent advances in ZIFs research which leads to future directions for further research in this field.

Keywords: zeolitic imidazolate frameworks (ZIFs), method, factors, application

Abstrak

Kerangka kerja zeolit imidazolat (ZIF) adalah subkelas kerangka kerja logam organik (MOF) yang telah menarik perhatian kerana sifat uniknya seperti permukaan yang luas, saiz liang yang boleh dilaraskan dan mempunyai kestabilan terma dan kimia yang sangat baik. Ulasan ini bertujuan untuk membincangkan ZIF dengan satu dan pelbagai penyambung yang telah dilaporkan sebelum ini. Sintesis ZIF boleh dicapai melalui pelbagai kaedah seperti solvoterma, hidroterma, ionoterma, bantuan gelombang mikro, sonokimia, sintesis kontra-resapan dan mekanokimia. Kajian ini membincangkan kelebihan dan kekurangan setiap kaedah serta

menyediakan analisis yang kritikal tentang keberkesanan sesuatu kaedah. Faktor sintesis ZIF juga dikelaskan kepada beberapa jenis seperti pelarut organik, bahan tambahan, kepekatan, suhu, variasi garam logam dan masa tindak balas. Tambahan pula, kertas kerja ini membincangkan beberapa aplikasi ZIF, termasuk kesan ZIF terhadap penyerapan bahan pencemar, pemangkin dan sistem penghantaran ubat. Kertas kajian ini juga meringkaskan kemajuan terkini dalam penyelidikan ZIF yang membawa ke menyalurkan hala tuju masa depan untuk bidang ini dengan lebih lanjut.

Kata kunci: kerangka zeolit imidazolat, kaedah, faktor, aplikasi

Introduction

ZIFs emerges as a promising subfamily of MOFs that combines the advantages of zeolites and MOFs. ZIFs shows high thermal and chemical stability due to the tetrahedral metal-nitrogen bonds, high porosity, and tunable surface area which is achieved by simple modification of the imidazolate linkers or combined mixed linkers. ZIFs are constructed from transition metals like Zn^{2+} and Co^{2+} bridged to N-donor atoms of

the imidazolate linkers in a tetrahedral cluster to form a larger and neutral framework (Figure 1). ZIF structures closely resemble aluminosilicate zeolites, where the tetrahedral metal centres of ZIFs mimic the role of silicon, while the N-donor atoms of the imidazolate linkers replace the function of oxygen in zeolites. It was found that the bonding angle of ZIFs was similar to that of zeolites, Si-O-Si, at 145° [1–3].

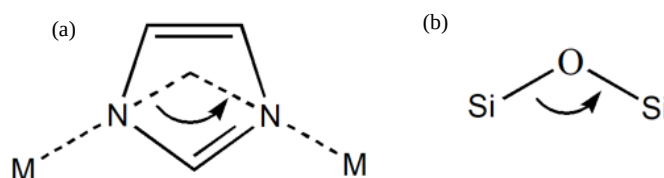


Figure 1. (a) The bond angle in the imidazolate linker, M-Im-M is 145° (b) Tetrahedral arrangement of ZIFs where blue: Metal (Zn, Co) green: imidazolate [3]

Therefore, it is not surprising that ZIFs showed advantages of both zeolites and MOFs. Most ZIF materials demonstrated high thermal stability between 200 to 400 $^\circ\text{C}$ under nitrogen. The frameworks also remained stable in various organic solvents at high temperatures and ambient conditions. For example, a chemical stability experiment for ZIF-300, ZIF-301, and ZIF-302 was conducted by immersing the materials in boiling water for seven days. The PXRD patterns of these materials were in good agreement with the simulated PXRD patterns generated from SCXRD [4]. Moreover, the frameworks did not show any compositional changes in organic solvents such as methanol and benzene at 65 and 85 $^\circ\text{C}$ within the seven days, indicating that ZIFs were chemically stable materials [1]. The coordination ability between organic linkers and metal centres influenced the formation of ZIFs and offered more controllability and flexibility compared to zeolites. The pore size of ZIFs can be modified by incorporating more than one type of imidazolate linker into the framework along with

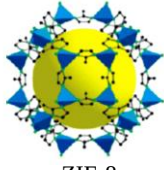
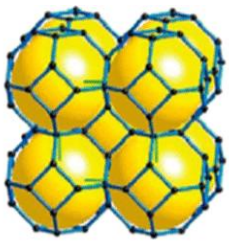
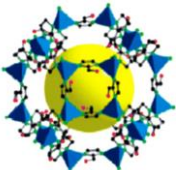
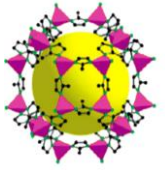
multiple functional groups. It is also possible to synthesise ZIFs with a wide range of imidazolate linkers and metal centres to create similar topologies. For example, ZIF-8 was synthesised using 2-methylimidazole (2mIM) and zinc nitrate tetrahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$), shared the same sodalite (sod) topology as ZIF-67, which is composed of 2mIM and Co^{2+} centres [5] (Table 1). A similar case occurred with ZIF-90, where this framework was synthesised using 2-imidazolecarboxaldehyde (ICA) and ($\text{Zn}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$), resulting in a **sod** topology [6].

In this review, we pay full attention to the research developments in the synthesis and possible applications of ZIFs. We first consider the previously reported single and mixed-linkers of ZIFs, a range of preparation methods (synthetic routes) of ZIFs, encompassing both solvent and solvent-free approaches. In addition, the effects of synthesis conditions on the formation of ZIFs including the main applications in some promising areas

were also highlighted in the write-up. The review is proposed to provide guidance and highlight the

significant to the readers for the future development of ZIF materials.

Table 1. Comparison between crystal structures of ZIF-8, ZIF-90 and ZIF-67 with **sod** topology [5]

Metal centre	Linker	Structure	Topology
Zn^{2+}	 2mIM	 ZIF-8	 sod topology
Zn^{2+}	 ICA	 ZIF-90	
Co^{2+}	 2mIM	 ZIF-67	

Solvent methods of ZIFs

The solvothermal method is a well-known technique to synthesise MOFs and ZIFs by mixing organic linkers and metal ions in a specific reaction solvent such as dimethylformamide (DMF), diethylformamide (DEF) and *N*-methyl-2-pyrrolidone (NMP). The synthesis reaction is conducted in a closed space environment, such as NMR tube, microplates and vials that can withhold high temperatures (80 to 140 °C) to generate autogenous pressure [7]. These conditions enhance the solubility of reactants and accelerate the interaction between metal centre and organic linker during the reaction. The synthesis of ZIFs typically takes place over a period of 12 to 96 hours [1–4,6,8]. High boiling point solvents may degrade at high temperatures, forming amine as side product that act as nucleophilic bases, facilitating the crystallisation process [3]. Consequently, ZIFs synthesised via the solvothermal method consistently yield highly crystalline products. The synthesis of ZIF-1 to ZIF-12 was reported in 2006 in which the initial development of ZIFs were focused

with Zn^{2+} and Co^{2+} as the metal centres, and the different types of imidazolate linkers such as imidazole (IM), benzimidazole (bzIM) and 2mIM). In 2008, a group of researchers introduced two types of imidazolate linkers bonded in a framework which was used to successfully synthesise ZIF-60 to ZIF-80 in different solvents at the reaction temperature beyond 80 °C [1,5].

Undeniably, the solvothermal method allows the formation of highly crystalline and phase-purified ZIFs by increasing the solubility of reactants [9]. However, organic solvents are not environmental-friendly and cost-redundant for large-scale synthesis of ZIFs. In addition, large solvent molecules are difficult to remove from the framework's pores. Therefore, the hydrothermal synthesis method has been applied to reduce the usage of toxic organic solvents by replacing them with water [10,11]. This method is usually performed after the successful development of established ZIFs through solvothermal method. Several factors that need to be considered before synthesising

ZIFs using the hydrothermal method includes the concentration of imidazolate linkers, the addition of additives and zinc source [12]. These factors are crucial to ensure crystallinity of ZIFs can be achieved.

from solvothermal synthesis methods, the ionothermal method has been employed to produce ZIF material that utilises ionic liquid or eutectic mixtures [13,14]. It should be mentioned that an ionic liquid can act simultaneously as a solvent and a structure-directing agent (template) to avoid the competition between the solvent framework and the template-framework that existed in hydrothermal preparation due to the presence of hydrogen bonding. This method is performed under ambient pressure in an open system, which eliminates the risks of high autogenous pressure in a sealed autoclave [15]. In addition, the advantage of using ionic liquids as solvent is that they can be reused for further synthesis reactions [14]. ZIF-8 was also synthesised under the ionothermal method using a deep eutectic solvent by heating the mixture of $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, 2mIM linker, and tetrabutylammonium bromide (TBAB) while stirring at 40 °C [16]. The coordination between the 2mIM linker and Zn^{2+} was initiated by the hydrogen bond interaction between the N-H bond of 2mIM linker and the halide ion of TBAB, which promoted the deprotonation of the 2mIM linker. The obtained material possessed a high BET surface area of $1486 \text{ m}^2 \text{ g}^{-1}$, higher than the ZIF-8 material synthesised under the hydrothermal method ($460 \text{ m}^2 \text{ g}^{-1}$). The crystallinity of synthesised ZIF-8 under the ionothermal method was also comparable with the simulated PXRD pattern of ZIF-8 [16]. ZIF-67 was synthesised under the same method in 1-ethyl-3-methylimidazolium bromide ([emim])Br ionic liquid. The mixtures of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, 2mIM linker, and ([emim])Br ionic liquid were stirred, and the solution was transferred to a 30 mL Teflon-line autoclave at 140 °C for several minutes. The PXRD pattern of ZIF-67 synthesised from the ionothermal method was in good agreement with the PXRD pattern of ZIF-67 synthesised from the solvothermal method [17].

Microwave-assisted synthesis is an alternative method that is analogous to conventional synthesis methods. The fundamental concept behind microwave-assisted

synthesis is that microwave heating is produced from the interaction of electromagnetic radiation with mobile electrical charges between solid or soluble conducting ions and polar solvent molecules [15]. In the solid phase, the material's electrical resistance produced the electric current, which contributed to the heating effect on conducting or semiconducting materials [18–20]. While in solution phase, high temperatures could increase the collisions between aligned polar molecules with the rapidly changing electromagnetic field, hence increasing the kinetic energy of these molecules [15,18]. This has led to the generation of microwave heating due to molecular friction. The microwave-assisted method is carried out at a temperature above 100 °C in a short time within one hour. The feasibility of the microwave-assisted method has been explored for the preparation of ZIF-11. In the first step, bzIM linker and zinc acetate dihydrate ($\text{Zn}(\text{OAc})_2 \cdot 2\text{H}_2\text{O}$) were dissolved in the solvent mixture (MeOH, toluene and ammonium hydroxide). The solution was placed in a Teflon liner and microwave- heated at 100 °C for 60 minutes. ZIF-11 displayed a regular hexagonal shape with an average size of $5.0 \mu\text{m}$ and possessed high BET surface area of $745 \text{ m}^2 \text{ g}^{-1}$ [21]. ZIF-8 synthesised under this method exhibited good crystallinity and BET surface area, which is consistent with the results obtained from solvothermal and hydrothermal methods. This material also showed good performance as an adsorbent for the adsorption of Congo Red dye (CGR) and Rhodamine B (RhB), with a removal efficiency achieved beyond 87% [22].

The third synthesis method of ZIFs is the sonochemical method, which is related to the molecules' chemical and physical changes after ultrasonic irradiation. The alternate pressure from ultrasonic irradiation is responsible for generating acoustic cavitation. The hot spots around the liquid were developed in the acoustic cavitation and provided extraordinary high temperature and pressure, which initiated the chemical reaction of ZIFs [18,23,24]. This is an eco-friendly method for producing ZIFs over a short period of time. The sonochemical method is performed using a direct immersion ultrasonic horn or ultrasonic cleaning bath. ZIF-8 was obtained under ultrasound radiation with various power settings (98 kHz, 300 kHz, and

1 MHz) and frequencies (10, 20, and 30 watts) [25]. The crystallinity, purity, and yield of ZIF-8 were maintained using this method. However, ultrasound has a significant impact on the nucleation step and contributes to the fast production of the nucleation centre. This resulted in a reduction of the particle size in ZIF-8 [25]. Thin film ZIF-8 was prepared under this method by dissolving 2mIM linker in a mixture of deionised water and TEA while stirring for 10 minutes at room temperature [26]. Then, the zinc hydroxide solution was immersed in the respective 2mIM linker solution before being sonicated at room temperature. The frequency and power of the sonicator was set at 40 kHz and 100 watts. The crystal size of ZIF-8 was found to increase as the reaction time proceeded from 5 minutes to 60 minutes. Moreover, the PXRD patterns of ZIF-8 became more sharp and intense, resulting from the prolonged sonication time [26].

Contra-diffusion is another method that can be used to produce existing ZIFs. During the first stage of the reaction, the metal and organic linker solutions are diffused in opposite directions along the support or the defects in the membrane grains, forming a thin membrane layer [27]. Moreover, the contra-diffusion approach is an alternative method for reducing the reaction rate and producing a thin and defect-free membrane. A well-intergrown and continuous ZIF-8 layer is formed on the metal ion side surface of the poly(4-vinylpyridine) brushes as a result of a combination of surface graft and the optimal addition of sodium formate into the ligand. ZIF-8/poly(4-vinylpyridine) membrane demonstrated excellent reusability as an adsorbent material for iodine, with a removal efficiency of 73.4% after five cycles [28]. In 2019, a group of research successfully formed a uniform layer of ZIF-8 on porous polyvinylidene fluoride (PVDF) ultrafiltration membranes. The membranes were separated and filled with solutions of 2-methyl imidazole and zinc nitrate. Both the processes of solution diffusing into the membranes crystallisation took place at room temperature which resulted in an excellent performance of the ultrafiltration process [29]. ZIFs can be synthesised using various methods and it is evident that further development can be undertaken to reduce the reaction time, increase production yield and improve the porosity of the framework.

Solvent-free method of ZIFs

Mechanochemical synthesis is another method that could produce ZIFs. Compared with conventional synthesis methods, mechanochemical synthesis is an approach that uses little solvent and energy and reduces reaction time. This synthesis method uses a ball mill to grind metal salt and organic linker without the involvement of solvent or heat [18]. The mechanical energy generated from grinding would minimise the particle size to promote the interaction between the organic linker and metal ions [15]. Mechanochemical synthesis was conducted at room temperature by converting ZnO to ZIF-8. The solution of ZnO and 2mIM linker were placed in a 300 mL ceramic pot before the ceramic pot was rotated at 100 rpm [30]. The transformation of ZnO to ZIF-8 produced a lower yield product after prolonged milling exposure. The addition of $(\text{Zn}(\text{OAc})_2 \cdot 2\text{H}_2\text{O})$ was essential to promote acid dissolution of ZnO and facilitate the complex formation between ionised Zn and the 2mIM linker [30]. Thus, adding a small liquid could promote the formation of ZIF and improve the morphology of ZIF-8 under mechanochemical synthesis from agglomerated amorphous ZIF to dendritic porous architecture (Chen *et al.*, 2014). The glass-forming ZIF-62 was synthesised by the mechano-synthetic route using liquid-assisted grinding. All starting materials, that are ZnO, 2mIM, and IM linkers, were mixed together in a 10 mL stainless steel grinding jar and was shaken for 30 minutes. In this synthesis method, ZnO was used instead of $\text{Zn}(\text{NO}_3)_2 \cdot 2\text{H}_2\text{O}$ or ZnCl_2 to avoid the formation of HNO_3 or HCl by-products that would have resulted from the metathesis of Zn salts with IM and bzIM linkers. This is because the acid by-products would digest ZIF to its starting materials. The mechanochemical method would reduce the amount of starting materials and reaction time for the production of materials compared with the solvothermal synthesis method. Although the crystal size of ZIF-62 obtained from the mechanochemical method is smaller than the conventional synthesis method [31].

Synthesis of single linker ZIFs

Up until 2023, the synthesis and characterisation of ZIFs had been achieved. The pioneering work in this field was led in 2006, when they successfully synthesised 12 ZIFs.

These included ZIFs with Zn^{2+} centres, namely ZIF-1 to ZIF-10, as well as those with Co(II) centres, specifically ZIF-9 and ZIF-11. This achievement was accomplished through the use of a variety of imidazolate linkers, such as IM, bzIM, and 2mIM, resulting in the formation of novel ZIF materials with distinct topological structures [3]. There are six ZIF structures, all composed of Zn^{2+} centres with imidazolate linkers, each displaying different three-dimensional (3D) topologies, including **crb**, **dft**, **cag**, and **mer** s depicted in Figure 2.

Notably, ZIF-1, ZIF-2, ZIF-3, ZIF-4, ZIF-10, and ZIF-14 were crystallised in various space groups and crystal systems, which were influenced by the molar composition of the reaction conditions. Consequently, this variance resulted in the formation of diverse topologies. In particular, ZIF-10 was found to crystallise within a tetragonal crystal system with a space group of $I4/mmm$. Among these ZIFs, ZIF-10 exhibited a notably high crystal volume of approximately $14,211(2) \text{ \AA}^3$.

This exceptional volume can be attributed to the high concentration of imidazolate linker which led to the formation of bigger framework. All the nitrogen atoms from imidazolate are coordinated to Zn^{2+} centres in a tetrahedral geometry resulting in the formation of an 8-membered ring and a 4-membered ring of **mer** and **dft** topology [3,5]. The pore diameter of **mer** topology is $12.12 \text{ \AA}$, which is more significant than **dft** topology, $8.02 \text{ \AA}$ [32]. ZIF-8 and ZIF-67 are well-known frameworks that consist of a similar linker, 2mIM. They adopted the **sod** topology with 4- and 6-membered rings, despite having different kind of metal centres. This topology featured one kind of vertice and edge with a pore diameter of $11.6 \text{ \AA}$, which received a considerable attention from many researchers to utilise these frameworks in many promising applications. The surface areas of ZIF-8 and ZIF-67 are $1947 \text{ m}^2 \text{ g}^{-1}$ and $1676 \text{ m}^2 \text{ g}^{-1}$, respectively, surpassing those of other ZIFs with single linker [3,5].

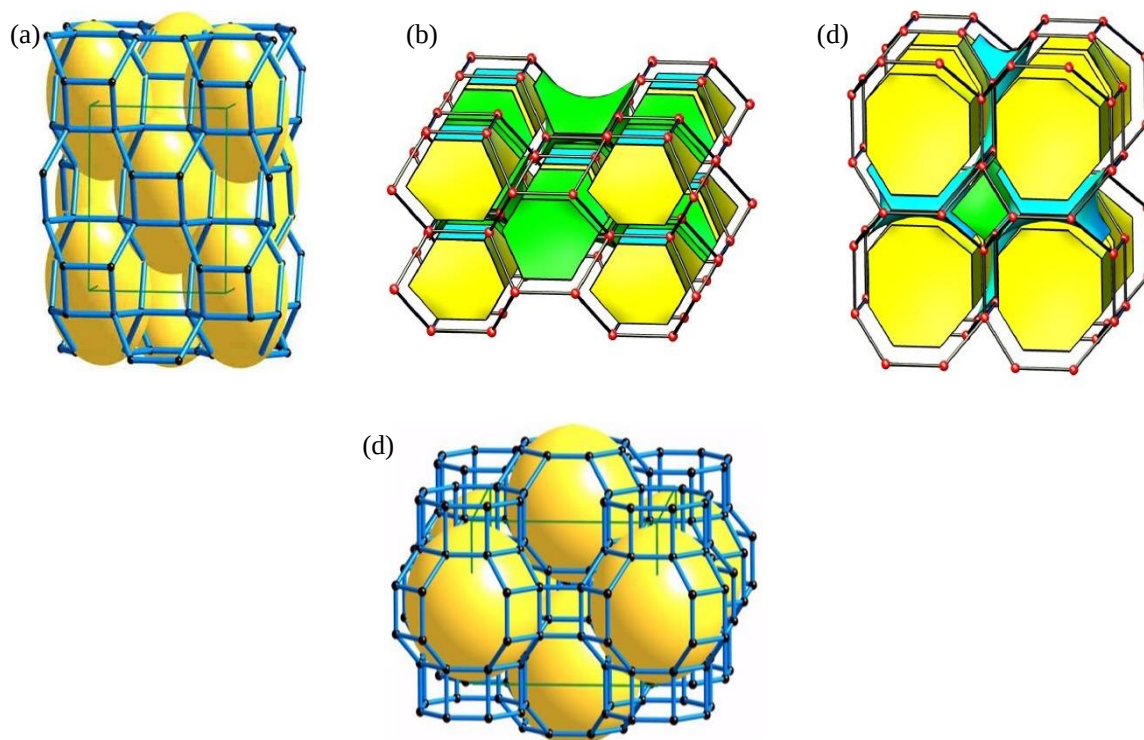


Figure 2. Topologies of the network structures; (a) ZIF-4, **cag**; (b) ZIF-1 and ZIF-2, **crb**; (c) ZIF-3, **dft**; (d) ZIF-10, **mer** [3]

Meanwhile, ZIF-7 and ZIF-11 are comprised of similar metal centres joined by bzIM linkers, but these frameworks adopted different topologies (ZIF-7: **sod** and ZIF-11: **rho**), as shown in Figure 3. The introduction of bzIM in the framework allows for the formation of a larger topology due to the functionalisation of the imidazole linker with benzene rings at 4th and 5th positions. The crystal systems for ZIF-7 and ZIF-11 are hexagonal and cubic, with space groups of $R\bar{3}$ and $Pm\bar{3}m$, respectively. Based on SCXRD results, ZIF-11 was proven to have a high crystal volume of about 23,787(14) Å³, in contrast to

ZIF-7 (7,214(14) Å³). The topology of ZIF-11 (**rho**) is considered a large topology in the presence of 4-, 6-, and 8-membered rings, compared to the **sod** topology. Therefore, ZIF-11 was successfully crystallised in a larger framework, over longer reaction time and medium temperature of 100 °C, which led to a slow crystallisation process and higher surface area of the framework. Both the ZIFs have exhibited high chemical stability and the crystallinity of the frameworks were maintained after immersing them in boiling benzene, water, methanol, and ethanol for seven days.

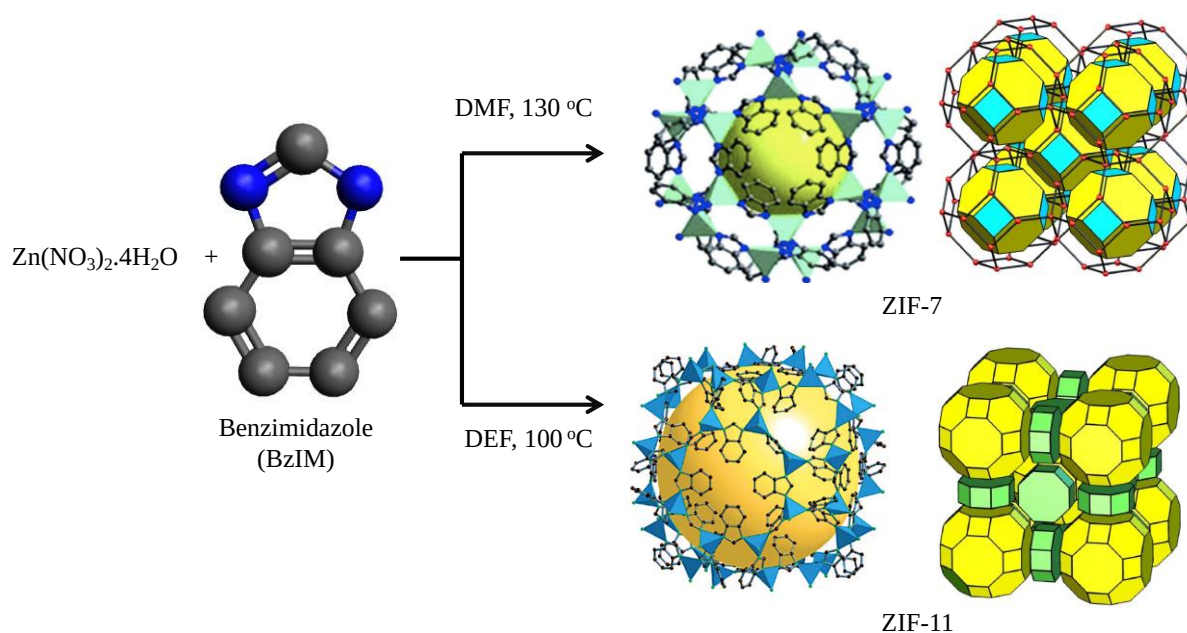


Figure 3. The formation process of ZIF-7 and ZIF-11 which produced different kind of topology [3,5]

In 2008, new porous ZIFs with high surface area were reported, namely ZIF-95 and ZIF-100 (Figure 4). ZIF-95 was constructed using zinc nitrate tetrahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$) and 5-chlorobenzimidazole (5cbIM). ZIF-95 crystallises within the tetragonal space group, displaying $I4/mmm$ symmetry, resulting in an underlying net topology symbolised as **poz**. In contrast with ZIF-95, ZIF-100 featured a tetrahedral metal centre with zinc trimethafluorosulfonate ($\text{Zn}(\text{O}_3\text{SCF}_3)_2$). SCXRD results revealed that ZIF-100 shared the same crystal system as ZIF-11 and has $Im\bar{3}$ symmetry, with an

extensive cell volume of approximately 372,932(4) Å³, which proved ZIF-100 to be a large inorganic framework. It is believed that the incorporation of 5cbIM into the framework led to the formation of a new topology, facilitated by the functionalisation of bzIM with a chlorine atom at the 5th position. Figure 4 illustrates the ZIF-100 underlying net topology, denoted as the **moz** topology, with an inner diameter of the framework exceeding that of the faujasite (**fau**) topology, measuring approximately 35.6 Å [2].

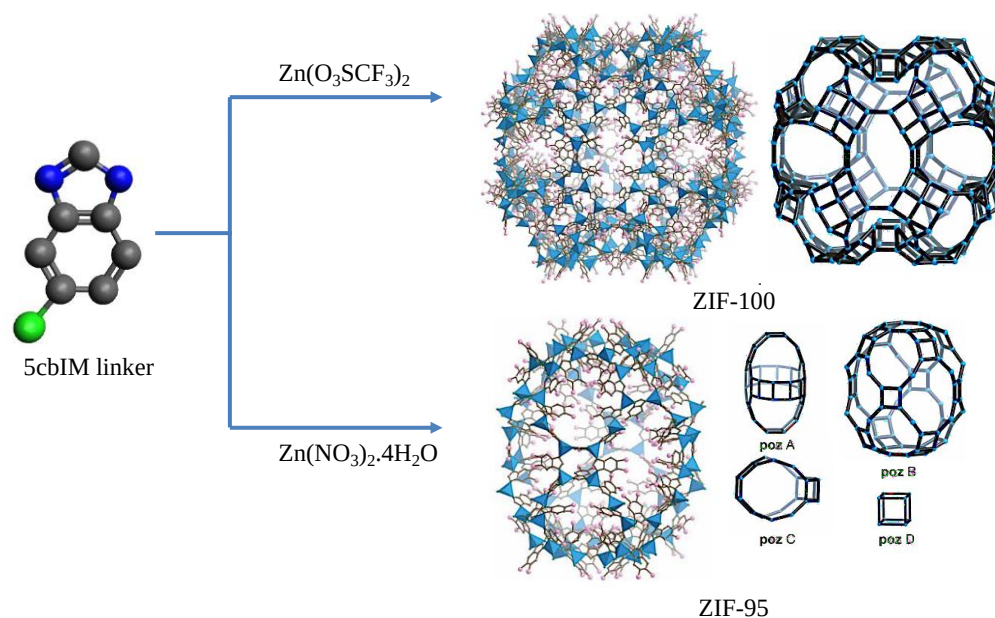


Figure 4. The structure of ZIF-95 and ZIF-100. Both the ZIFs were made up of different kind of metal salts with 5cbIM linker , forming different types of topologies [2].

Notably, ZIF-95 encompasses two distinctive types of cages with varying inner diameters. The initial cage, known as **poz A**, possesses an inner diameter measuring 25.1 x 14.3 Å, making it roughly the same size as the super cage in the **fau** topology. The second cage of ZIF-95 is **poz B** with 30.1 x 20.0 Å of inner diameter, significantly greater than the diameter of the **fau** topology, which is around 14.1 Å. The extended framework was linked by the tetra coordinates of Zn^{2+} centre for ZIF-95, resulting in the creation of an exceptionally expansive **poz** topology. This topology accommodates two large cages, with the first **poz** cage (**poz A**) followed by the second **poz** cage (**poz B**), both cages containing 8-, 10-, and 12-membered rings. Importantly, each imidazolate linker in ZIF-95 exhibits specific steric indexes (δ), as indicated in Figure 5.

The steric index is used to measure the size and shape of imidazolate linkers, taking into account their van der Waals volume and length. Imidazole linkers with increased bulkiness exhibit a higher steric index value (δ) compared to smaller imidazole linkers,. The strategic introduction of bulkiness at the 4th and 5th positions of imidazolate linkers has profound impact, resulting in the formation of large cages containing more than 8-membered rings within the frameworks. This led to the

formation of entirely new and extensive underlying net topologies, which is a direct outcome of incorporating imidazolate linkers with high steric indices [8].

Synthesis of mixed-linker ZIFs bearing two different imidazolate linkers

There are several advantages in mixed-linker ZIFs compared to single linker ZIFs. Incorporating two or more different imidazolate linkers in the framework enables the fine-tune of surface area and pore size by selecting imidazolate linkers of varying size and length. For instance, the gas separation efficiency is significantly enhanced in mixed-linker ZIF-7-8, whereas the incorporation of the bulkier bzIM linker, along with the 2mIM linker, results in the formation of a larger aperture [33]. The introduction of different functional groups derived from distinct imidazolate allows for the tailored design of functionality within the frameworks, providing a variable surface environment. This mixed-linker strategy is exemplified by introducing two different imidazolate linkers with diverse functional group, such as combining 2mIM with 2-aminobenzimidazole (2amBzIM) in the ZIF-8 framework [34]. This approach serves to improve the permeability and selectivity for CO_2 capture. Moreover, the frameworks that contained three imidazolate linkers

leads to formation of a substantial topology, as observed in ZIF-412, -413, and -414, generating a novel underlying topology [8]. This unique topology demonstrated capability in capturing large molecules,

such as xylene, which further proves the capability of mixed-linker ZIFs to capture molecules like xylene which is comparably difficult to attain in a single linker ZIFs.

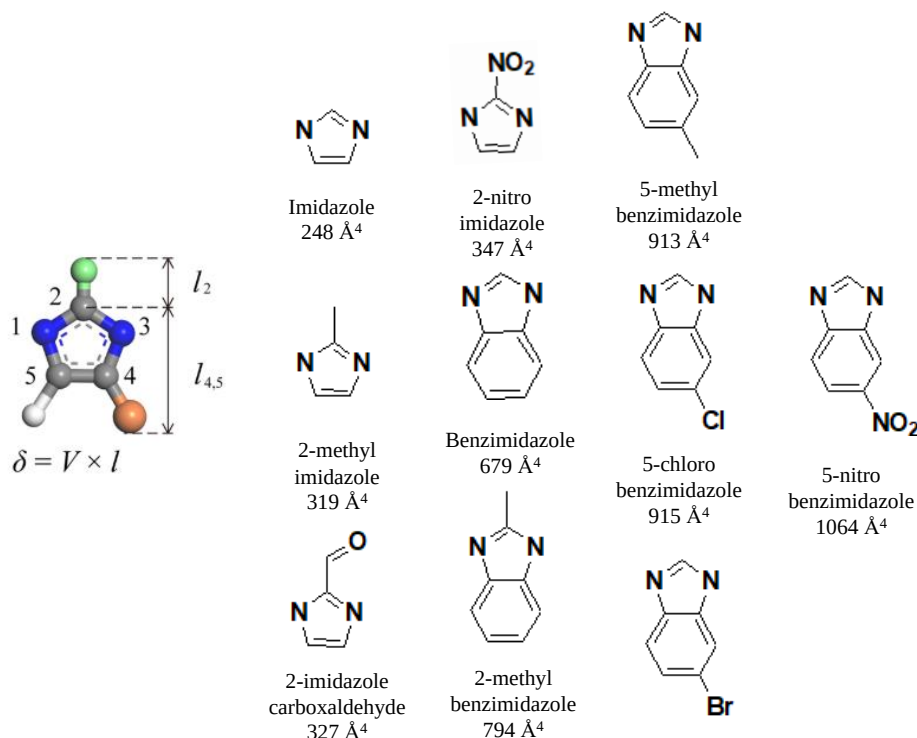


Figure 5. Steric index for imidazolate linkers based on the van der Waals volume (V) and length (l) [8]

Incorporating multiple linkers within a single framework proves to be an efficient strategy for the development of novel ZIFs with diverse functionalities, adjustable porosity, customisable topology, and enhanced performance tailored for specific applications. Mixed-linker ZIFs were synthesised based on the chabazite, **cha** topology, which involves the utilisation of bulky imidazolate derivatives such as 5-methylbenzimidazole (5mbIM), ZIF-302; 5-chlorobenzimidazole (5cbIM), ZIF-301; and 5-bromobenzimidazole (5bbIM) for ZIF-300. These derivatives were employed with 2mIM to form coordination bonds with Zn²⁺ centres [4]. ZIF-300 and ZIF-302 were crystallised in trigonal crystal system, and the space group associated with the crystals was *R*-3. Consequently, these ZIFs were classified as part of the isorecticular series of mixed-linker ZIFs.

The isorecticular framework constitutes of a series of compounds sharing the same topology while featuring organic linkers with varying functionalities and sizes [35,36]. Based on NMR analysis, bzIM derivatives were the dominant organic linkers in the frameworks compared to the 2mIM linker, even though the molar composition of metal to organic linkers maintained an equivalent ratio for both ZIF-300 and ZIF-301. This finding was further supported by SCXRD results, demonstrating that all the organic linkers were bound to the tetrahedral Zn²⁺ clusters. The resulting 3-periodic frameworks exhibit the **cha** topology, where the use of water as a co-solvent plays a crucial role in forming specific cavities, as shown in Figure 6. These cavities were composed of two distinct types: a *cha* [4¹²6²8⁶] cavity (the symbol [m^n], signifying the presence of n faces with m -membered rings), which is described as an 8-membered ring in this topology. Here 5mbIM, 5cbIM

and 5bbIM linkers are situated within this cavity. In contrast, derivatives of 2mIM or bzIM linkers are positioned at the edge of **cha** cavities, connecting to the two 6-membered rings of *hpr* cavities [4⁶²] (small cage). In addition, all of these frameworks remained stable when subjected to boiling water for seven days,

maintaining their crystallinity, as evident from experimental PXRD patterns. Furthermore, these ZIFs demonstrated type-III isotherms as a result of incorporating hydrophobic functionalities into the frameworks, thereby enhancing the overall stability of the frameworks [4].

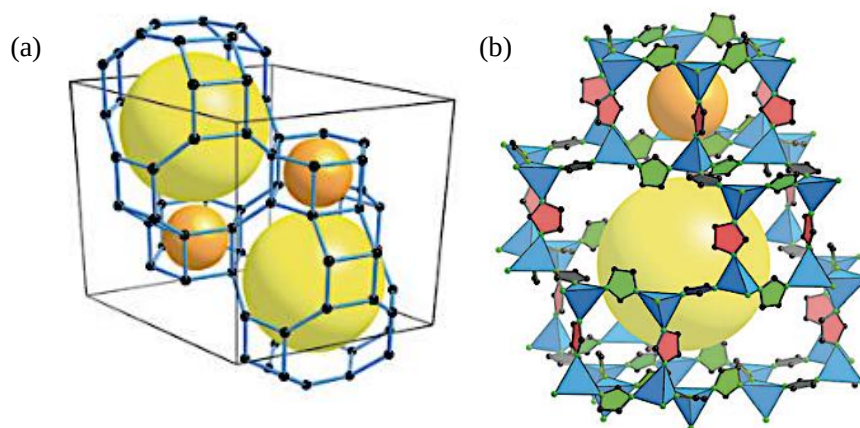


Figure 6. (a) Ball and stick model represent **cha** topology composed of two types of cavities *hpr* (large) and *cha* (small). (b) The **cha** topology of ZIF-300 and ZIF-301. Greyish-blue and red imidazolate linkers represent 2mIM and bulky imidazolates (5bbIM, 5cbIM and 5mbIM) respectively whereas green imidazolate linkers indicated the position for non-specific linkers either 2mIM or bzIM derivatives can occupy in this position [4, 37].

The isorecticular series of ZIFs were successfully synthesised using 2-nitroimidazole (2nIM) with different types of imidazolate derivatives ranging from polar (-CN, ZIF-82; -NO₂, ZIF-78) to non-polar functionalities (-CH₃, ZIF-79; -Br, ZIF-81; -Cl, ZIF-80). These ZIFs formed definite topology with broad channels and large pore diameter [1]. In particular, the exact topology of the framework structures was constructed with different functionalities of cavities and different sizes of organic linkers, which determined the isorecticular series of ZIFs, as illustrated in Figure 7. ZIF-79, ZIF-80, ZIF-81, ZIF-82 and ZIF-78 were synthesised by solvothermal method using different solvent and period of reactions. These ZIF compounds crystallised in a hexagonal crystal system, sharing the common space group of *P6₃/mmc*. Intriguingly, despite the introduction of diverse functionalities of the imidazolate linkers, these five mixed-linker ZIFs exhibited a gmenilite (**gme**) topology [2,3,5]. As shown in Figure 7, the **gme** topology consists of *hpr* cages

where the 2nIM linker occupies along the cage edges, while the imidazolate linker with varying functionalities are within the cavities of *kno* cages with pore diameter ranging from 7.1 Å to 15.9 Å.

Remarkably, functionalised imidazolate linkers found in ZIF-78 and ZIF-79, such as 5-nitrobenzimidazole (nbIM) and 5mbIM contributed to smaller pore diameters around 7.1 Å and 7.5 Å, respectively, achieving a slightly tilted orientation in the topology. ZIF-82 containing smaller imidazolate linkers, 4-cyanoimidazole (cnIM) and 2nIM, featured larger pore diameter around 12.3 Å [1]. In addition, PXRD of these ZIFs remained unchanged even after exposure to boiling benzene, water and methanol. This demonstrated that ZIFs are extremely stable under diverse environmental conditions. The integration of multiple imidazolate linkers within a single framework emerges as an efficient strategy for attaining variable functionalities, larger cages and varying pore sizes of the frameworks.

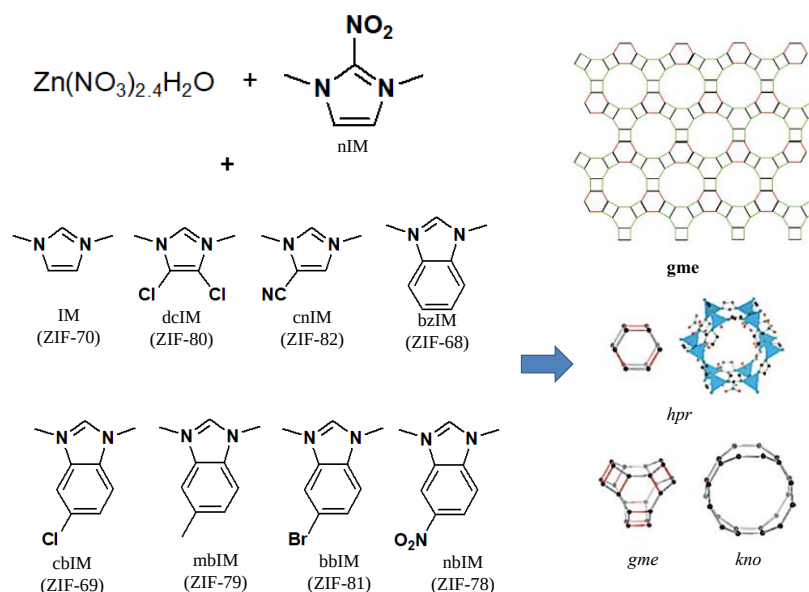


Figure 7. Imidazolate linkers and their abbreviations (IM: Imidazole; dcIM: 4,5-dichloroimidazole; 4cnIM: 4-cyanoimidazole; 5cbIM: 5-chlorobenzimidazole; 5mbIM: 5-methylbenzimidazole; 5bbIM: 5-bromobenzimidazole; 5nbIM: 6-nitrobenzimidazole) reacted with Zn^{2+} and 2-nitroimidazole (2nIM) to form **gme** topology. The **gme** topology consist of several cavities such as *hpr*, *kno* and *gme* as illustrated on the left side [2,3,5].

In 2017, a group of researchers obtained new ZIFs by introducing two bulky imidazolate linkers into the framework, named ZIF-516 and ZIF-586. The crystal structure of ZIF-516 consisted of 5bbIM and 5mbIM linkers, while ZIF-586 featured 5mbIM and 2mbIM linkers, linked together by tetrahedral Zn^{2+} clusters. These ZIFs were crystallised in a tetragonal crystal system; however, both ZIFs were arranged into different space groups (ZIF-516: $P4_32_12$ and ZIF-586: $P4_2/ncm$). Despite the distinct space groups, these frameworks

were classified under the same underlying net topology, **ykh**, containing large cages ranging from 22.1 to 22.3 Å. Figure 8 shows the **ykh** and **moz** topology of ZIF-516, ZIF-586 and ZIF-408. The introduction of 5bbIM, 5mbIM, and 5cbIM with functionalised imidazolate linkers at 4th and 5th positions resulted in the formation of large and small cages comprising of 3-, 4-, 10-, 12-, and 14-membered rings, generating large topologies such as **ykh**, **poz**, **moz**, and **zea** [8].

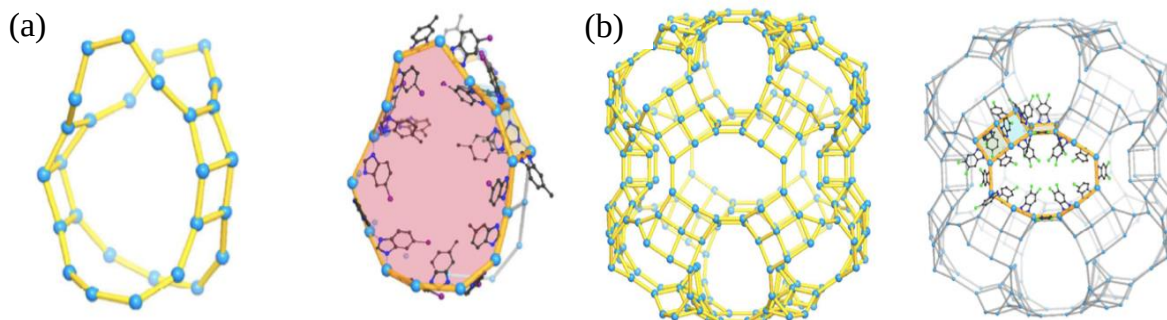


Figure 8. (a) **ykh** topology of ZIF-516 with 3-, 4-, 10-, 12-, and 14-membered rings. (b) **moz** topology of ZIF-408 consists of 4- and 12-membered rings. C: black, N: blue, O: red, Cl: green and Br: violet [8]

ZIF-412, ZIF-413, and ZIF-414 formed a new underlying topology, **ucb**, featuring several types of membered rings ranging from 4-, 6-, 8- to 24-membered rings. The cage size was measured at 45.8 Å, making it the largest cage within the topology (Figure 9). The building units for ZIF-412, ZIF-413, and ZIF-414 was a combination of multiple bulky imidazolate linkers (6nbIM, bzIM, 5mbIM) with small imidazolate linkers (2nIM and IM). These compounds crystallised in a cubic

system with the space group, $Fm\bar{3}m$. The combinations of small and large steric indices facilitate the formation of large and small cages in ZIFs, resulting in topologies like **moz** (41.2 Å) and **ucb** (45.8 Å). Therefore, it is important to incorporate small imidazolate linkers like imidazole alongside other bzIM derivatives with high steric index to enable the creation of extensive crystal structures [8].

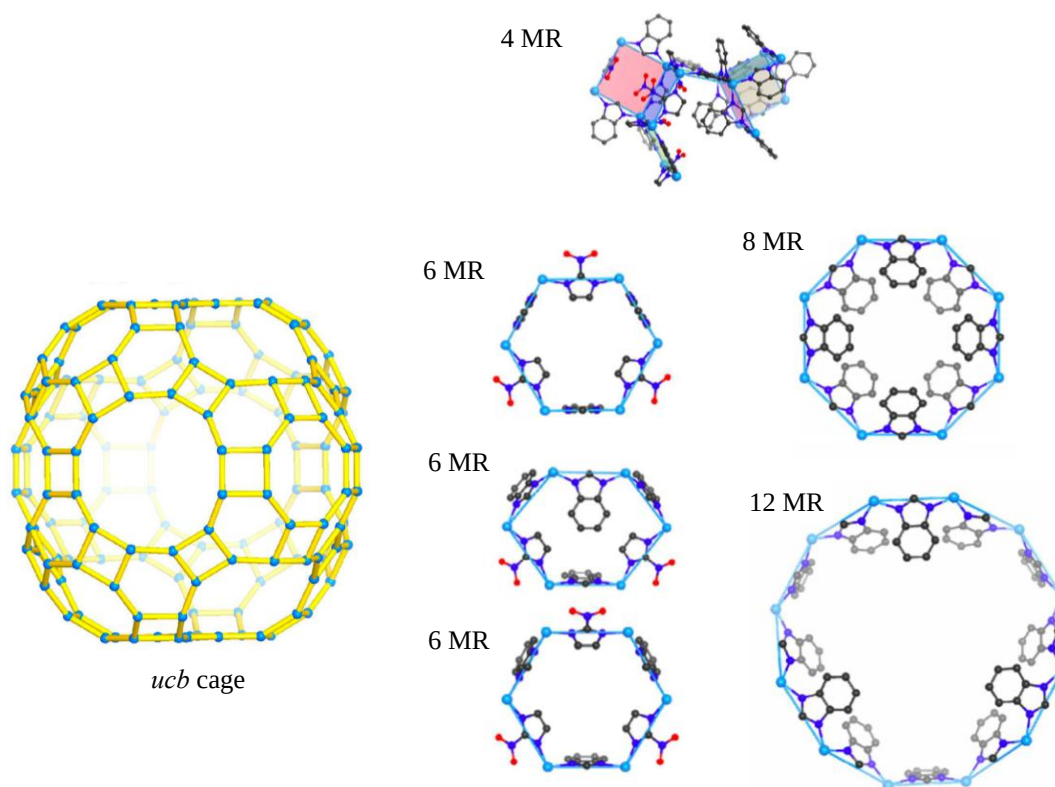


Figure 9. The **ucb** topology of ZIF-412, ZIF-413 and ZIF-414 [8]

Factors in the formation of ZIFs

There are several prevalent factors affecting the formation of ZIFs, such as (i) the effect of organic solvents, (ii) effect of additives, (iii) the effect of concentration, (iv) the effect of temperature, (v) the effect of metal salt variation and (vi) the effect of reaction time on synthesis. Among these, it is believed that the reactant concentration and the type of solvent significantly impact the crystallinity of newly synthesised ZIFs.

Effect of organic solvents

Solvents play a critical role in the deprotonation process of imidazolate linkers, influence the rate of reactions, and affect the size of ZIF crystals. High-boiling-point solvents such as dimethylformamide (DMF), dimethylacetamide, and diethylformamide are widely employed as the primary solvents for the synthesis of ZIFs. The boiling points allow hydrolysis to occur at elevated temperatures, converting them into primary amines. This, in turn, facilitates the deprotonation of imidazole linkers and influences the bonding formation

between metal centres and imidazolate linkers, resulting in the formation of large crystals [4]. The use of DEF for the synthesis of ZIF-11 is due to its high boiling point solvent (178.3 °C), which allows for control of the nucleation growth of crystals and reduces the formation of cracks in the crystals [38,39].

Dimethylsulfoxide (DMSO) has also been employed as a solvent for synthesizing ZIF-8 and ZIF-67. These frameworks were synthesised at room temperature using DMSO, marking the first synthesis involving DMSO as a solvent. They found that the crystal sizes of ZIF-8 and ZIF-67 obtained using DMSO were smaller compared to those produced in the presence of methanol [40]. For instance, the average particle size of ZIF-67 in DMSO after 30 minutes was only 30 to 50 nm, whereas ZIF-67 in methanol had an average particle size of approximately 306 nm (Figure 10) [41]. Consequently, methanol has been chosen as the primary solvent for the room-temperature synthesis of ZIFs. In addition, ZIF-71, comprising of Zn^{2+} centres and 4,5-

dichloroimidazole (dcIM), was synthesized at room temperature in 15 ml of methanol [42]. The precursors were mixed, and the reaction was allowed to proceed for 24 hours at room temperature. A centrifugation process was applied to recover the crystals. Methanol-based ZIF-71 exhibited a higher surface area of approximately $1118.65 \text{ m}^2 \text{ g}^{-1}$ compared to ZIF-71 synthesised with DMF solvent.

Furthermore, ZIF-8 was synthesized at room temperature in the presence of methanol. The mixture solution of $Zn(NO_3)_2 \cdot 6H_2O$ and 2mIM linker was stirred at 200 rpm for 60 minutes, resulting in an average crystal size of 1 μm . Another ZIF-8 synthesis was conducted at room temperature with the same solvent at 1000 rpm for five minutes. However, the crystal size of ZIF-8 obtained at a higher stirring rate was smaller [43]. This is because the stirring rate influences the rate of crystallisation, which in turn determines the ultimate crystal sizes of ZIFs [44].

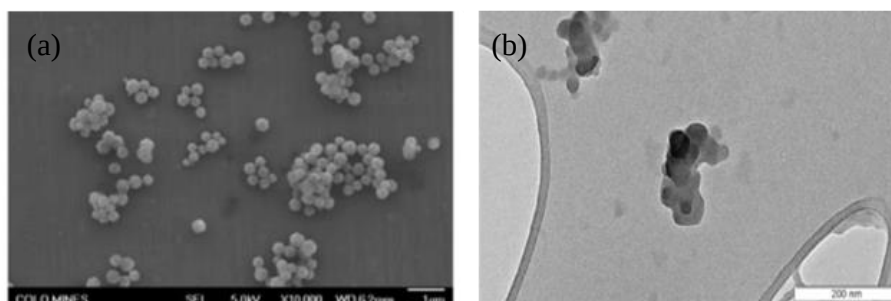


Figure 10. SEM images of ZIF-67 crystals synthesised using (a) methanol and (b) DMSO [41]

Effect of additives

Water is considered an eco-friendly and ideal solvent for the green synthesis method to fabricate ZIFs. However, a high concentration of water in the reaction system can lead to the hydrolysis of Zn^{2+} ions, leading to an increase in by-products of the reaction. Besides, using a high amount of water in the ZIF formation can slow down the crystallisation of ZIF due to the high pK_a value in the aqueous solution. This situation typically occurs when the concentration of imidazolate linkers is lower in the system, slowing down the reaction rate between metal centres and imidazolate linkers [43, 44].

In addition, it can be challenging to synthesise ZIF with a low concentration of precursors in water at room temperature without a base [45, 46]. Therefore, some base agents have been introduced in the synthesis reactions of ZIFs to deprotonate imidazole linkers and accelerate the reaction rate in the water-based synthesis method [47]. ZIF-8 was prepared using an aqueous mixed base, employing ammonium hydroxide (NH_4OH) and triethylamine (TEA) as deprotonating agents. [48]. The mixed base system was believed to have high potential for promoting the formation of ZIF framework at room temperature within several minutes, based on previous works. The synthesis reaction was completed

by stirring the solution mixture for 10 minutes at room temperature [49,50]. As shown in Figure 11, ZIF-8 particles in the presence of TEA formed aggregated sub-micrometer crystals. ZIF-8 particles synthesized without TEA showed a more uniform cubic shape and had a similar morphology to those synthesized using the solvothermal method.

The use of water as a solvent significantly enhances the thermal stability and morphology of the framework. The addition of bases as deprotonation agents in chemical

reactions involving organic linkers has resulted in rapid nucleation rates, leading to the formation of small ZIF crystals [51]. The inclusion of additives in the ZIF synthesis is crucial for reactions that use water as the primary solvent. In contrast to solvothermal reactions, these additives serve as deprotonating agents that initiate the crystallisation process, thereby accelerating the reaction and achieving a high yield. Although most of the products are formed within the nanometre size range, they are well-suited for applications requiring nanosized materials, such as catalysts and drug delivery [52].

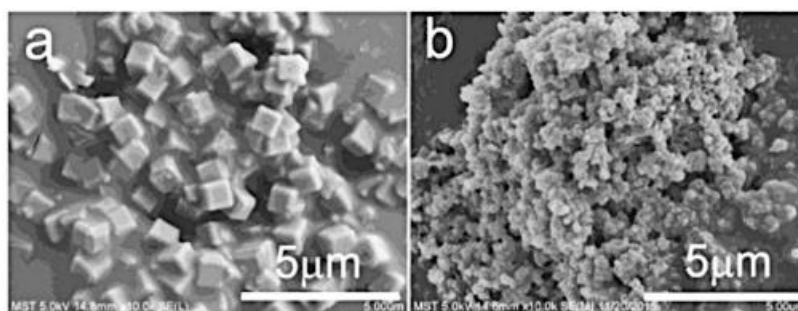


Figure 11. SEM images of ZIF-8 (a) in the absence of TEA and (b) in the presence of TEA [53]

Effect of concentration

The solvothermal method is as well-established as the conventional method to synthesise highly crystalline ZIFs. In this method, a low-molar composition of Zn^{2+} and imidazolate linkers is used to form the framework, with organic amine solvents (DMF, DEF, and DMA) acting as nucleophilic agents in the reaction. Most of the mixed-linker ZIFs were synthesised within the range of 2 to 4 moles under the solvothermal conditions. Pure microcrystals of ZIFs were formed using a low-molar composition of Zn^{2+} :2mIM, demonstrating that a high concentration of imidazolate linkers is not required for the solvothermal method [5]. The presence of organic amine solvents is sufficient to initiate the nucleation process in the synthesis reaction [51]. Despite the promising development of ZIFs, the use of organic solvents contributes to environmental pollution. Therefore, there is a strong desire to use water as a solvent to address the environmental issues and reduce costs.

Nonetheless, using a high amount of water as a solvent can lead to the hydrolysis of Zn^{2+} , increasing the

production of by-products and slowing down the rate of deprotonation of the 2mIM linker [45, 47]. To accelerate the reaction rate, a high amount of imidazolate linkers is required in hydrothermal synthesis to increase the basicity of the aqueous solution. The morphology and sizes of crystals heavily depend on the molar composition of metal ions and organic linkers. Thus, conducting multiple synthesis reactions with different concentrations is crucial to obtain ZIF, as determined by SEM and PXRD analysis. In a previous study in 2018, the effect of the molar composition of 2mIM/ Zn^{2+} on the properties of ZIF-8 was investigated [44]. ZIF-8 was synthesised with five different molar compositions of 2mIM/ Zn^{2+} , ranging from 1, 2, 4, 8, to 16 in 50 mL of methanol at room temperature [44]. Good yield and crystallinity of ZIF-8 were obtained with molar composition of Zn^{2+} /2mIM below 8. Molar compositions of 2 and 4 resulted in ZIF-8 with a truncated dodecahedral morphology. In contrast, different morphologies were observed with higher molar compositions (8 and 16) of 2mIM/ Zn^{2+} , as shown in Figure 12.

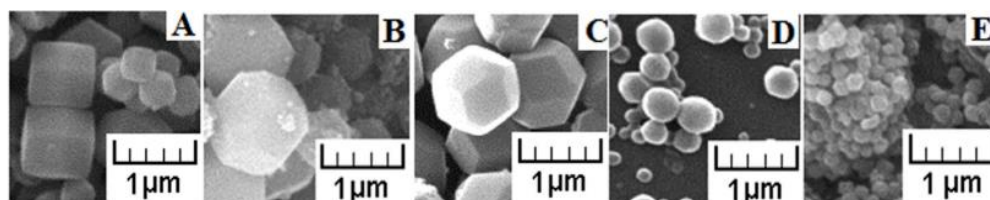


Figure 12. SEM images of different ZIF-8 samples with different molar ratios of $\text{Zn}^{2+}/2\text{mIM}$ of (a) 1, (b) 2, (c) 4, (d) 8 and (e) 16 [44].

One limitation was that high concentrations of the 2mIM linker led to the formation of a framework with lower surface areas and particles aggregation, as evidenced by SEM analysis. Meanwhile, molar compositions of $\text{Zn}^{2+}/2\text{mIM}$ in the range of 2 to 4 yielded the highest surface areas for ZIF-8, measuring around $1268 \text{ m}^2 \text{ g}^{-1}$ and $1943 \text{ m}^2 \text{ g}^{-1}$, respectively. These results indicated that moderate molar compositions of $\text{Zn}^{2+}/2\text{mIM}$ were capable of producing highly crystalline frameworks with a maximum surface area for ZIFs [3,54]. A higher content of imidazolate linkers in the reaction system

accelerated the rate of the nucleation process and also influenced the particle sizes of the frameworks [44]. ZIF-8 was also synthesised in a microemulsion mixture of n-heptane and n-hexanol in TritonX-100, employing different molar compositions of Zn^{2+} to 2mIM (1:2, 1:5, 1:8, and 1:16) at room temperature (Figure 13) [55]. Uniform cubes of ZIF-8 nanoparticles were obtained with a molar ratio of 1:2/ $\text{Zn}^{2+}:2\text{mIM}$ and the particle size decreased from 110 nm to 40 nm as the concentration of the 2mIM linker increased [56,57].

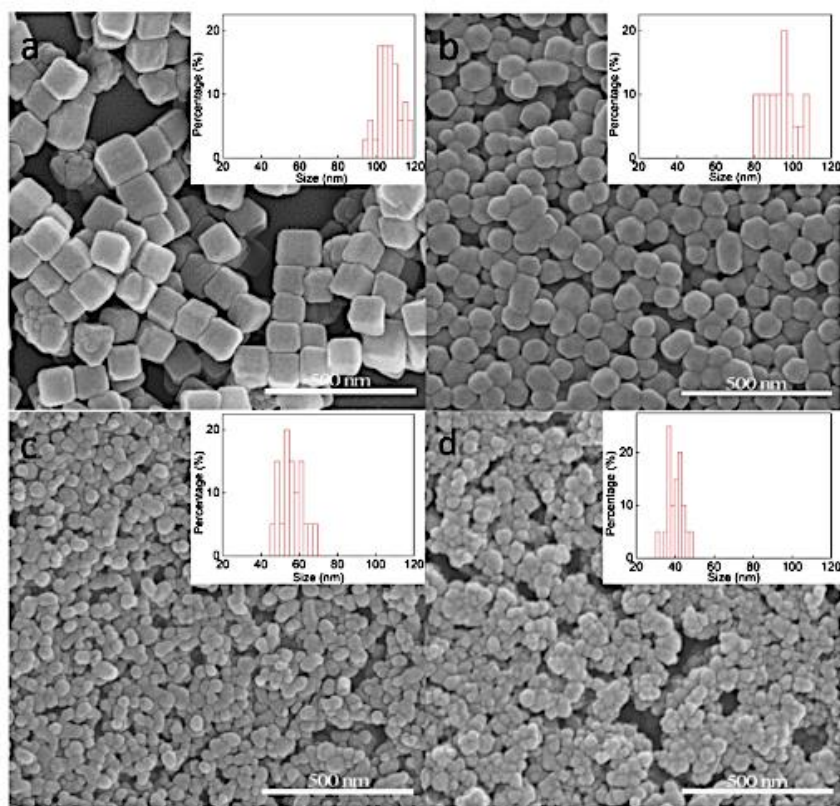


Figure 13. FESEM images of ZIF-8 nanoparticles obtained from different molar compositions of $\text{Zn}^{2+}:2\text{mIM}$ (a) 1:2 (b) 1:5 (c) 1:8 (d) 1:16 [55]

The broader peak widths of the XRD patterns of ZIF-8-110 and ZIF-8-90 in Figure 14 was attributed to the formation of small crystal size in the samples, as a result from the high concentration of the imidazolate linker [55]. The construction of the framework is a meticulous

process that necessitates the use of the appropriate molar composition of organic linkers and metal salts. This parameter is highly dependent on the specific synthesis method employed, as it significantly impacts the crystallinity and particle size of ZIFs.

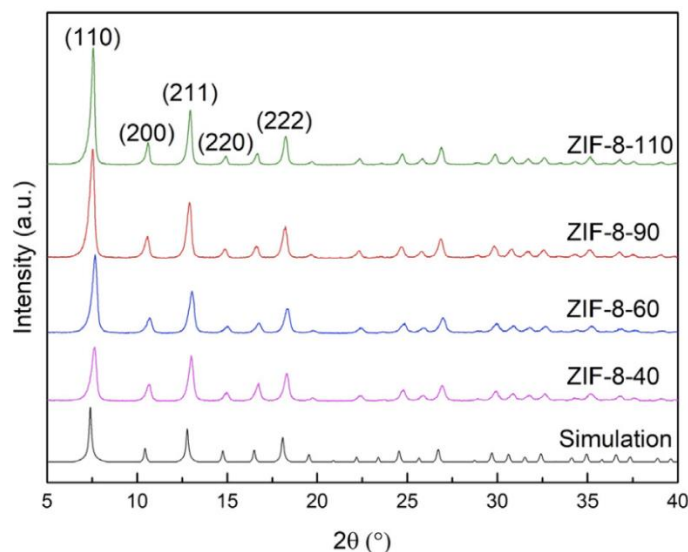


Figure 14. PXRD patterns of ZIF-8 nanoparticles with different sizes based on FESEM images (a) ZIF-8-110, (1:2) (b) ZIF-8-90, (1:5) (c) ZIF-8-60, (1:8) (d) ZIF-8-40, (1:16) [55]

Effect of temperature

The temperature of the chemical reaction is a critical factor in the formation of ZIF particles. Previous studies have reported that synthesis work conducted at different temperatures affects the crystallinity of ZIFs. ZIF-8 was prepared at varying temperatures (80, 100, 120, and 140 °C) under microwave-assisted solvothermal methods in methanol within 30 minutes [48]. A high crystallinity of ZIF-8 was observed based on PXRD patterns at 120 °C and 140 °C, which is close to the reference pattern of ZIF-8 synthesised under the solvothermal method. Meanwhile, the synthesis of ZIF-8 at a temperature lower than 100 °C was unable to generate a high crystallinity of ZIF-8 [48]. This is because the temperature is directly proportional to the pressure of the reaction under the microwave system and the solvothermal method [55]. In addition, the hydration of the metal salts decreases as the temperature of the reaction increased, as it is associated with entropic gains from the thermodynamic control leading to the release of water molecules from metal sites. This allowed more

opportunity for deprotonated linkers to bond with metal sites [48].

Two ZIF-8 compounds were prepared at two different temperature, room temperature (ZIF-8-RT) and 140 °C (ZIF-8-HT) via hydrothermal synthesis [58]. Sharp peaks were observed in the PXRD patterns of ZIF-8-HT and ZIF-RT. Nonetheless, the full width half maximum values (FWHM) of the PXRD patterns of these ZIFs recorded different values at 7.3° [58]. The FWHM value of ZIF-8-HT was 0.14°, which is smaller than the FWHM value of ZIF-8-RT, which was around 0.20°. A larger FWHM value is responsible for peak broadening in PXRD patterns. The synthesis of ZIF-8 at higher temperature produced better crystallinity, due to the induction of high vapour pressure, as well as increased density, the vacant sites of metal centres, and the dimensionality of the frameworks [58]. The homogeneity in the heating process is a crucial nucleation rate for the construction of ZIFs [59, 60].

Effect of metal salt variations

The construction of ZIFs results from the formation of chemical bonds between the metal ions and the linkers. The types of metal salts used play a crucial role in determining the size of the ZIFs. According to Pearson's acid-base concept, metal salts with different counter ions possessing varying interaction strengths influence the nucleation rate. Higher concentration of metal salts and organic linkers in the reaction system contribute to an increased nucleation rate, leading to the formation of more nuclei which resulted in the production of large amounts of tiny crystals [61, 62]. Zinc acetate, $\text{Zn}(\text{OAc})_2$ was the prominent metal salt for synthesising ZIF-8 in the hydrothermal method [47]. The morphology of the synthesised ZIF-8 particles using ZnSO_4 and $\text{Zn}(\text{OAc})_2$ exhibited a rhombic dodecahedron for molar ratios of $2\text{mIM}/\text{Zn}^{2+}$ between 20 and 35. Furthermore, the formation of ZIF crystals is dependent on the molar composition of the precursors in the reactions. When ZIF-8 was synthesised using a high molar ratio of $2\text{mIM}/\text{Zn}^{2+}$, truncated edges with bumpy surfaces were produced. In contrast, low molar ratios of $2\text{mIM}/\text{Zn}^{2+}$ resulted in rhombic dodecahedron morphology. As the molar ratio of $2\text{mIM}/\text{Zn}^{2+}$ decreased, the average size of ZIF-8 particles using ZnSO_4 also decreased from 1.64 μm to 231 nm.

Previous studies have highlighted that the size of ZIF particles depends on the molar ratio of precursors and the type of metal salts in the chemical reaction [47]. The morphology of ZIF-8 particles prepared from $\text{Zn}(\text{NO}_2)_3$ exhibited spherical and petal shapes, which is opposite to the findings obtained from the synthesis of ZIF-8 using $\text{Zn}(\text{OAc})_2$ and ZnSO_4 . ZIF-8 synthesised using $\text{Zn}(\text{NO}_2)_3$ showed better crystallinity framework than $\text{Zn}(\text{OAc})_2$ and zinc sulphate, ZnSO_4 , due to the high reaction temperature at 85 °C for 60 hours [46]. In terms of crystallinity, previous work has demonstrated that the high crystallinity of ZIF-8 could be obtained in the order of $\text{Zn}(\text{NO}_3)_2 > \text{Zn}(\text{OAc})_2 > \text{ZnSO}_4 > \text{zinc chloride}, \text{ZnCl}_2$. Different metal salts will influence the synthesis process of ZIFs due to variations in pH resulting from the anionic ions of metal salts. Among these metal salts, ZIF-8 using $\text{Zn}(\text{NO}_3)_2$ recorded high catalytic activity in Knoevenagel condensation reactions due to the high external surface area of the ZIF-8 crystal. $\text{Zn}(\text{NO}_3)_2$ is

composed of a soft acid metal ion, Zn^{2+} , with hard base anion, NO_3^- , which allows for more available vacant sites for the 2mIM linker to coordinate with Zn^{2+} ions, hence forming many nuclei and contributing to the framework's high surface area [46].

Effect of reaction time on synthesis

Another critical parameter to highlight for the formation of ZIFs is the effect of the reaction time on synthesis. It is widely accepted that a longer reaction time will yield higher quantity of products suitable for various promising applications. Previously, ZIF-8 was synthesised within 60 minutes using a sonochemical method under ultrasound irradiation, resulting in fine textural properties, however, with a low yield. The synthesis work conducted within three hours produced a high output of ZIF-8 crystal [25, 26]. Significant differences were observed between the short and long reaction periods of ZIF-8 from 5 minutes to 60 hours conducted in an aqueous medium. A longer reaction period resulted in ZIF-8 having a high surface area of 1027.20 $\text{m}^2 \text{g}^{-1}$ compared to the surface area obtained at five minutes, which was 878.59 $\text{m}^2 \text{g}^{-1}$. It is worth mentioning that reaction time is also interconnected with temperature; as they increase, better morphology is achieved and the product yield is enhanced [46].

ZIF-11 had different morphologies after being synthesised at 60 and 100 °C for 12 hours and six hours respectively. These shapes included rhombic dodecahedron shapes. The duration of the reactions strongly depends on the molar composition of the synthesis reaction, as demonstrated previously [40]. ZIF-11 was synthesised using three different molar compositions of $\text{Zn}^{2+}/\text{bzIM}$ (1:4, 1:8, and 1:12). The same rhombic dodecahedral was formed at low and high concentrations, but the products were formed at different times. ZIF-11 crystals were fully formed after 48 hours for the molar composition of $\text{Zn}^{2+}/\text{bzIM}$ at 1:4, which was attributed to the slow transition of pure phase crystalline of ZIF-11. In addition, pure crystalline ZIF-11 was achieved within 24 hours for high molar compositions of precursors. This demonstrates that the reaction duration depends on the molar composition and synthesis temperature, which influences the

recrystallisation and dissolution processes for the formation of ZIF [46].

Applications of ZIFs

ZIFs have been utilised in a wide range of applications owing to their exceptional chemical and thermal stability as well as flexible and adaptable frameworks that can be customised to suit specific applications. In this section, some of the significant applications of ZIFs are highlighted and discussed.

Adsorption of pollutants

Adsorption of pollutants is an alternative method for wastewater treatment due to its minimal production of secondary by-products and ease of operation. Activated carbon is a conventional adsorbent in wastewater treatment, and this adsorbent has a few limitations, including weak interactions with pollutants and

problems related to regeneration in practical applications. Therefore, MOFs and ZIFs have emerged as promising adsorbents for wastewater treatment [40]. The structures of MOFs and ZIFs are flexible, which allow the incorporation of additional functionalities, such as unsaturated metal centres and active functional groups, to achieve targeted interactions with pollutants. For instance, ZIF-8 demonstrated rapid adsorption of methyl blue (MB), achieving a remarkable adsorption capacity of approximately 1917.5 mg g^{-1} within just 60 minutes. Despite the smaller pore diameter of ZIF-8 compared to the size of MB molecules, the high adsorption of MB is likely attributed to the formation of ionic bonds between the metal centre of ZIF-8, Zn^{2+} , and SO_3^- from MB. Figure 15 shows the proposed adsorption mechanism between SO_3^- from MB and Zn^{2+} from ZIF-8 [63].

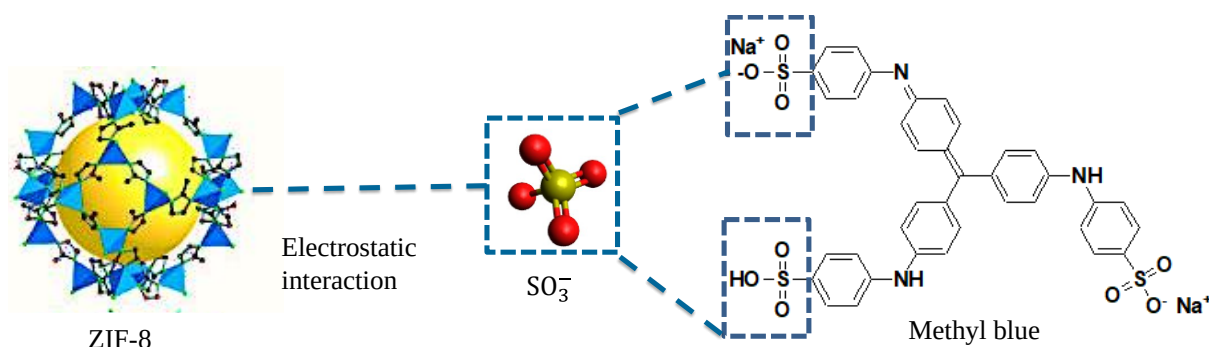


Figure 15. Adsorption mechanism between methyl blue and ZIF-8 [63]

Subsequent studies on the adsorption capabilities of Rhodamine B (RhB) and methylene blue (MB) have been previously explored. ZIF-8 was synthesised using ultrasound and a surfactant (Pluronic* P-123) at room temperature, resulting in ZIF-8 with a surface area of $745 \text{ m}^2 \text{ g}^{-1}$ [64]. Organic dyes such as RhB and MB are classified as larger organic dyes (molecular sizes approximately $1.59 \times 1.18 \times 0.56 \text{ nm}$ and $1.7 \times 0.76 \times 0.33 \text{ nm}$), preventing them from passing through the pore apertures of ZIF-8. Consequently, adsorption of RhB and MB occurred on the external surface of ZIF-8 in between 2 to 48 hours, with adsorption capacities of 25.0 mg g^{-1} and 46.6 mg g^{-1} , respectively [65,66]. This highlights the significance of specific functional groups in organic dyes that enable better adsorption with ZIF,

even when the molecule size exceeds the small micropores of ZIF-8.

ZIF-67 showed good adsorption performance with anionic dyes. The adsorption values obtained using ZIF-67 ranged from 37.7 mg g^{-1} for xylene cyanol (XCFF) to 800 mg g^{-1} for Cibacron Blue 3G-A (CB) and fluorescein angiography. High adsorption capacities with anionic dyes are due to the positive surface charges on the surface of ZIF-67, as confirmed zeta-potential values ranged from 2.88 mV to 14.37 mV in a basic solution (pH 7.00-10.00). It is noteworthy that water contact with the surface of ZIF-67 induces the

protonation of imidazolate linkers (2mIM-) and enhances the interaction between anionic dyes and ZIF-67, as depicted in Figure 16 [53, 64, 65]. It should be emphasised that the optimal pH of the aqueous solution for the adsorption studies depends on the types of pollutants.

ZIF-7 was used in the adsorption of trichloroethylene, and it was found that the optimal condition for conducting the adsorption study was low pH solution ($\text{pH} < 6.00$) within 120 minutes [67]. Under these conditions, ZIF-7 achieved a remarkable removal efficiency of approximately 96.29%, highlighting the enhanced removal efficiency of trichloroethylene in an acidic environment [68,69]. It is intriguing to note that the pH of the solution can influence the surface charge of the adsorbents and the degree of ionisation of the

solution, which, in turn, affects the adsorption of pollutants. In a separate adsorption study, malachite green (MG) was adsorbed using ZIF-67. Several parameters, such as temperature, time, and concentration, were considered to determine the optimal condition for the adsorption study. Notably, as the temperature increased from 20 to 60 °C, a substantial increase in adsorption capacity was observed [70]. The maximum adsorption capacity was recorded at 60 °C with an adsorption capacity value of $2500 \text{ m}^2 \text{ g}^{-1}$, making it one of the highest adsorption capacities among established adsorbents such as MIL-100 (Fe), chitosan beads, and commercial powder activated carbon [67]. A chemical interaction took place between the imidazole rings and MG via the π - π stacking interaction, which facilitated the adsorption of MG onto the surface of ZIF-67 [71, 72].

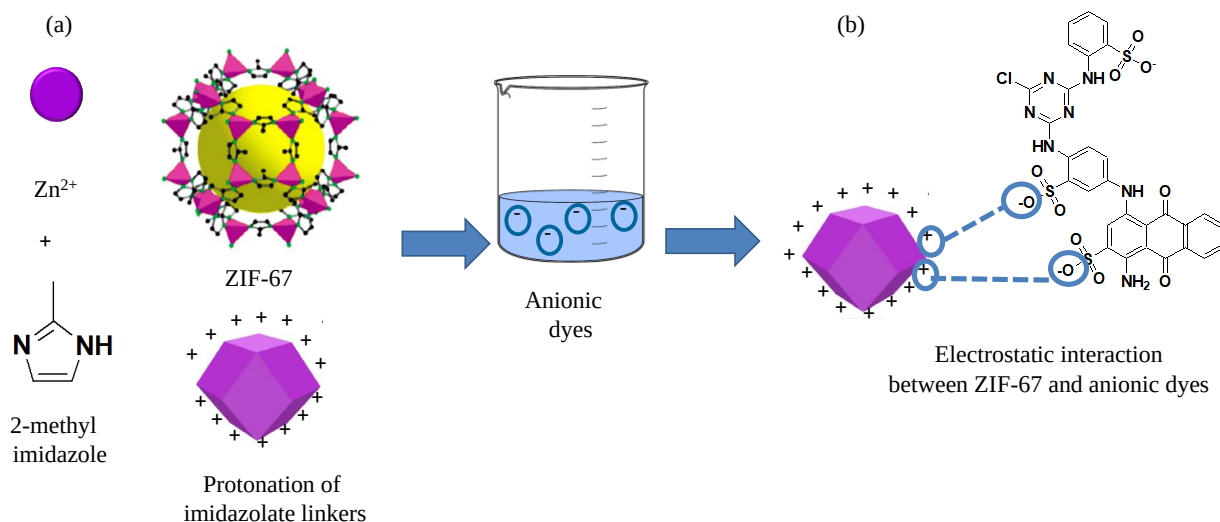


Figure 16. (a) Secondary building unit of ZIF-67 and (b) Interaction of ZIF-67 and anionic dyes [68, 69]

In another adsorption study, ZIF-67 showed excellent adsorption capacity towards Congo Red (CGR) from an aqueous solution, primarily attributed to electrostatic and π - π stacking interactions of the aromatic compound in CGR. Furthermore, the presence of Co^{2+} as the metal centre of ZIF-67 led to coordination between oxygen and nitrogen atoms from CGR, resulting in rapid adsorption in less than 40 minutes, even at a low concentration of 30 ppm. The impact of temperature was also evident, with an increase from 36.9 to 57.9 °C, leading to a significantly higher adsorption capacity of

up to 714.3 mg g^{-1} , indicating the promise of ZIF-67 as an effective adsorbent for CGR [70, 73].

Antibiotics have been extensively used for the treatment of human and animal diseases, owing to their effectiveness. However, a substantial portion of antibiotics is not fully absorbed by humans and animals, resulting in the release of these compounds into the environment [69]. Ofloxacin is a third generation of quinolone that was used in humans, aquaculture, and animal husbandry to prevent livestock disease. ZIF-8 is

used as an adsorbent to remove ofloxacin with an adsorption capacity of approximately $\sim 194.1 \text{ mg g}^{-1}$ at pH 7 with an adsorbent amount of 20 mg and 100 ppm of initial concentration [74]. Ofloxacin exists as zwitterionic state within the pH of 8.44 to 9.2, resulting in a strong electric attraction with ZIF-8. Concurrently, ZIF-8 exhibits a positive charge in a basic pH [75,76] as shown in Figure 17. The adsorption of ofloxacin involves various interactions, including strong hydrogen bonding between the fluorine atom in ofloxacin with C-NH bonds in ZIF-8, as well as complexation with unsaturated metal sites that facilitates interaction with ofloxacin. Additionally, the presence of 2mIM rings within the ZIF-8 framework and the benzene ring of

ofloxacin further enhance the adsorption capacity through π - π stacking interactions [74].

Similar chemical interactions were observed in the adsorption of norfloxacin using ZIF-8, a quinolone derivative [77]. ZIF-8 exhibited excellent adsorption efficiency at initial norfloxacin concentrations ranging from 10 mg L^{-1} to 30 mg L^{-1} . However, the efficiency of the adsorbent slightly diminished after 30 mg L^{-1} due to increased occupation of the available binding sites on ZIF-8 at higher norfloxacin concentrations. Furthermore, norfloxacin has a lower positive charge at pH levels between 4.5 to 6.2, allowing for enhanced adsorption with the positively charged ZIF-8 adsorbent due to lower electrostatic repulsion [78, 79].

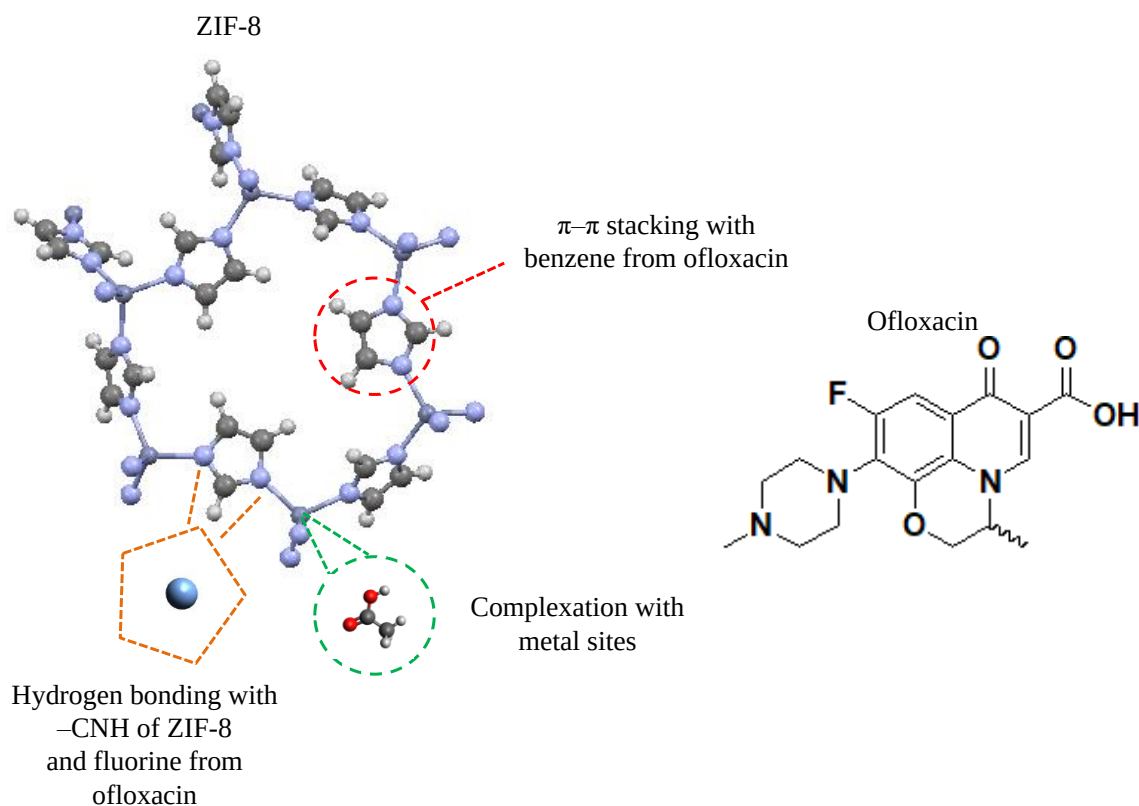


Figure 17. Mechanism of adsorption of ofloxacin with ZIF-8 [73-74]

Tetracycline (TC) and oxytetracycline hydrochloride (OTC) are commonly used antibiotics due to their effectiveness in treating bacterial infections and as veterinary drugs to promote animal growth [80]. However, only 30% of TC and OTC are absorbed by

animals, while the remaining antibiotics are discharged into the environment in their original form, posing significant threats to the environment [81]. To address this issue, ZIF-8 was used for the removal of simultaneous mixtures of TC and OTC antibiotics from

wastewater [80]. Fast adsorption was observed within 50 minutes at a pH 4 to 6, with an average simultaneous removal efficiency of 90.7% for TC and 82.5% for OTC at a concentration of 50 ppm. The impact of temperature on the simultaneous adsorption followed a pattern consistent with previous adsorption, indicating the reaction is an endothermic process. Higher temperatures led to rapid adsorption of TC and OTC due to molecular collision, which enabled greater interaction between adsorbates and the adsorbents [75,82].

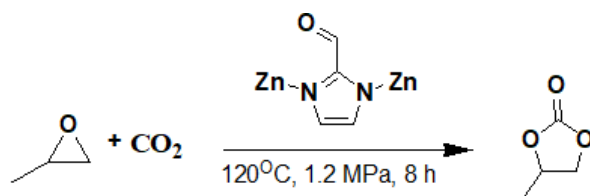
In conclusion, several ZIFs, particularly ZIF-8, have proven their potential as adsorbents for the removal of organic pollutants such as dyes and antibiotics. The maximum adsorption capacity is determined by the types of organic pollutants and various parameters within the adsorption experiments. These characteristics help to facilitate the chemical interaction that occurs between ZIFs and organic contaminants.

Catalyst

Aluminosilicate zeolites are well-established materials widely explored in many catalysis applications [83]. Owing to similar properties with aluminosilicate zeolites, ZIFs have emerged as efficient catalysts and co-catalysts for various catalytic reactions. Polylactide (PLA) is a widely recognised polymer derived from renewable resources that has received considerable attention due to its biocompatible properties [83–85]. Lactide (LA) is a monomer of PLA and undergoes ring-opening polymerisation (ROP) with a combination of a Lewis acid catalyst and organic bases to obtain cyclic PLA (cPLA) [86, 87]. ZIF-8 stands out as a promising Lewis acid catalyst for the polymerisation of L-lactide. This framework demonstrates exceptional thermal stability up to 400 °C based on TGA analysis. In addition, it remains insoluble in many common organic

solvents, signifying its chemical stability. In the previous study, ZIF-8 showed excellent catalytic activity at high concentrations ($[M]/[I] = 100$) and generated a high molecular weight of cyclic poly(L-lactide) (PLLA) of approximately 24.5 kg mol^{-1} with a conversion rate of 96%. This outcome aligns with MALDI-TOF mass spectrum results, where strong signals were observed for cyclic PLLA, indicating near complete conversion of L-lactide. The metal centre of ZIF-8, Zn^{2+} , functions as a Lewis acid site based on NMR spectroscopy, initiating chain growth by binding to the monomer. The Lewis acid sites are also working cooperatively with the active basic sites of ZIF-8, specifically the nitrogen atoms from the imidazolate ring, to catalyse the formation of cyclic PLLA via intramolecular transesterification. The PXRD pattern of the recycled ZIF-8 catalyst confirmed that the diffraction peaks remained unchanged after three runs of the ROP reaction, indicating no loss of catalytic activity during the recycling process [88].

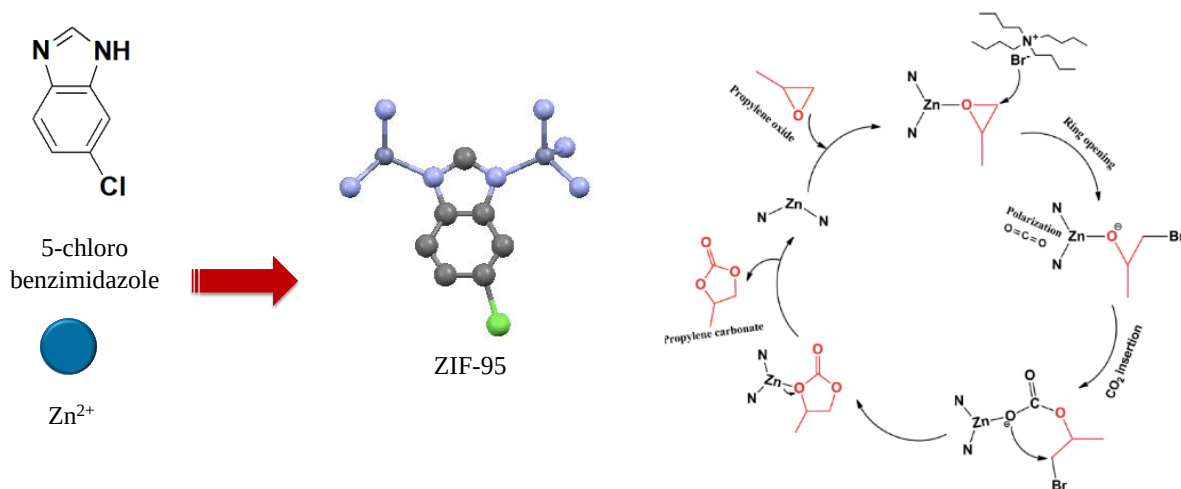
The utilisation of CO_2 represents a promising strategy for reducing atmospheric levels of CO_2 caused by human activities. As such, the synthesis of cyclic carbonates using CO_2 offers a particularly alternative pathway to reduce the atmospheric level of CO_2 [89]. Scheme 1 illustrates the application of ZIF-90 as a promising catalyst for cycloaddition, eliminating the need for additional co-catalysts. This approach resulted in 88% of propylene carbonate (PC) with 90% selectivity at 120 °C within eight hours. The aldehyde group of ICA within ZIF-90 stimulates CO_2 insertions, leading to the formation of a ring-opening intermediate. ZIF-90 emerges as a truly promising material for catalysis, as it contains ICA linkers that can replace co-catalysts in the catalytic reaction [90].



Scheme 1. Cycloaddition of propylene oxide (PO) and CO_2

In contrast with subsequent work in 2017, ZIF-95 showed excellent performance in the cycloaddition reaction, despite its structural similarity to ZIF-90. The maximum conversion of PO achieved with ZIF-95 was notably higher, reaching approximately 91%, with a selectivity exceeding 99% at the same temperature. Tetrabutylammonium bromide (TBAB) was used as a co-catalyst. The diffraction patterns for both frameworks remain unchanged even after they were

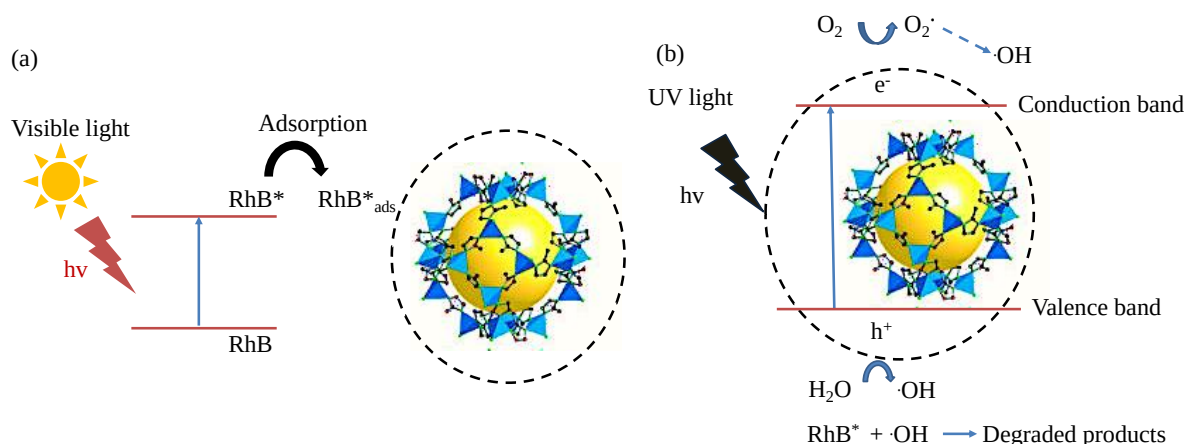
reused for more than three cycles at higher temperatures, indicating their robust chemical and thermal stability. ZIF-95 featured an unsaturated tetrahedral Zn^{2+} centre that functioned as a Lewis acid site, initiating the reaction on the oxygen atom of PC as an electrophilic attack [91]. In Scheme 2, the bromide anion from TBAB attacks the carbon atom of PO, leading to ring-opening intermediates [92].



Scheme 2. The mechanism of cycloaddition of propylene oxide (PO) using ZIF-95 as a catalyst to form propylene carbonate (PC), [93]

In addition, ZIF-8 is also used for the epoxidation reaction of menadione with hydrogen peroxide, H_2O_2 , achieving a remarkable 90% conversion to menadione-2,3-epoxide. This exceptional catalytic activity can be attributed to the presence of defects on the external surface of the framework, promoting interactions between H_2O_2 and the basic sites of ZIF-8. These basic sites include nitrogen atoms from the 2mIM ring and hydroxyl from methanol, facilitated via hydrogen bonding. The combination of the hydrophobic surface of ZIF-8 and the basic sites of the 2mIM ring contributes to a synergistic effect, resulting in nearly 100% selectivity [93]. Many ZIFs have been used as catalysts in the photodegradation of pollutants. Photodegradation is another alternative way to adsorb contaminants. The potential of ZIF-8 nanocrystals in the photodegradation

of RhB was examined under various conditions, such as dark, UV, and visible irradiation conditions [94]. At 430 nm, ZIF-8 nanocrystals exhibited excellent degradation of RhB. This phenomenon is due to as the transition of the excited electrons in ZIF-8 nanocrystals to the conduction band to react with surface oxidants (O^*) in order to form hydroxyl radicals (OH^*), facilitating the photodegradation of RhB (Scheme 3). The photodegradation process under visible light irradiation was slightly slower due to the large bandgap energy (5.6 eV) of ZIF-8 and the relatively low photon energy of visible light (1.8-3.9 eV) for electron excitation to occur within the framework. Consequently, there is a limitation in the production of the required amount of oxygen radicals for the photodegradation process [94].



Scheme 3. Proposed mechanism of photodegradation of RhB using ZIF-8 under (a) visible light and (b) UV light [94]

To address these challenges, ZIF-8 was successfully transformed by modifying its framework under thermal treatment to form a visible-light photocatalyst for decomposing gaseous formaldehyde [95]. This thermal treatment involved subjecting ZIF-8 nanocrystals to a temperature of 200 °C in the presence of air to convert the -N=C of the 2mIM linker into -N=C=O functional groups, thereby expanding the light absorption range from UV to infrared. The presence of the -N=C=O functional group enabled the decomposition of formaldehyde, achieving nearly ~100% efficiency within one hour under simulated sunlight. This result was supported by the optical absorption band of ZIF-8 nanocrystals, which appeared at 715 nm. ZIF-67 also exhibited excellent performance in broadening the absorption spectrum for the photocatalytic activity of Cr^{6+} reduction. The UV-Vis absorption spectra revealed three distinct absorption maxima at 1009 nm, 589 nm, and 265 nm, corresponding to the near-infrared (NIR), visible and UV light regions, with Cr^{6+} reduction efficiencies of 71.22%, 69.52%, and 40.72% after two hours. It is suggested that the 2mIM ligand in the framework is responsible for absorbing light from different sources, facilitating charge transfer to the metal centre to produce excited electrons for reduction of Cr^{5+} to Cr^{3+} [96].

The photocatalytic reduction of CO_2 offers a promising approach for generating hydrocarbon fuels and renewable sources. The mechanism of CO_2 reduction

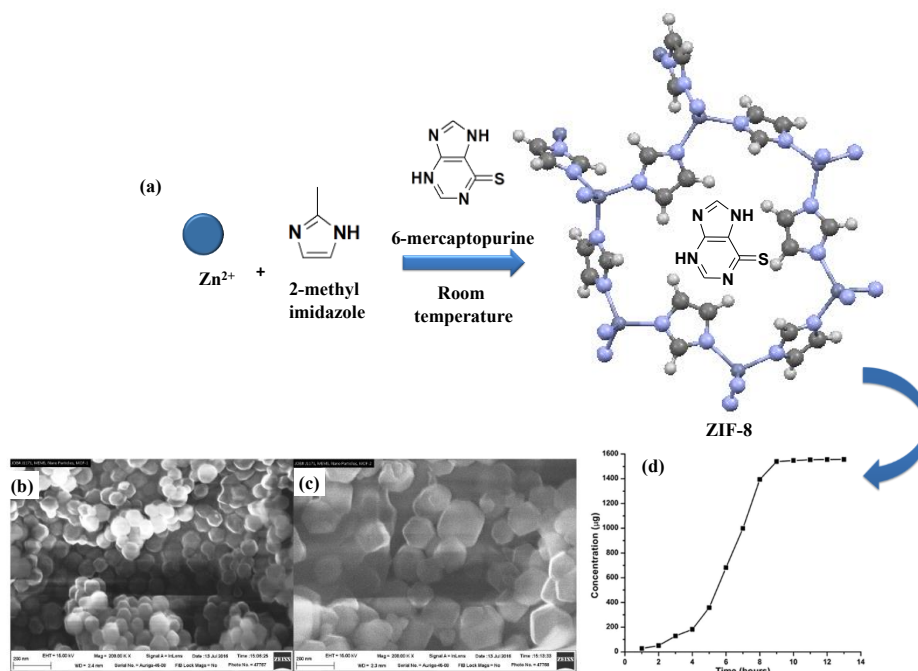
using photocatalysts depends on electron-hole separation, their lifetime, and CO_2 adsorption capacity [96]. ZIF-67 was used as a co-catalyst for CO_2 reduction at room temperature in the presence of photosensitizer ($[\text{Ru}(\text{bpy})_3]\text{Cl}_3 \cdot 6\text{H}_2\text{O}$) and electron donor (Triethanolamine) [97]. This study revealed that two-dimensional ZIF-67 with a leaf-like morphology exhibited a high CO_2 transformation rate and showed high CO_2 adsorption capacity. No decomposition occurred during the photocatalytic activity involving ($[\text{Ru}(\text{bpy})_3]\text{Cl}_3 \cdot 6\text{H}_2\text{O}$) and ZIF-67 at 580 nm, indicating excellent electron transfer efficiency from the photosensitizer to the co-catalyst. Additionally, the strong interaction between CO_2 molecules and Co^{2+} reduced to Co^+ , which facilitated the production of CO molecules for generating hydrogen gas, H_2 [98]. ZIF-8 was used as a catalyst to promote hydrogen production via sodium borohydride (NaBH_4) hydrolysis. ZIF-8 was synthesised using zinc hydroxide nitrate nanosheets ($\text{Zn}_5(\text{OH})_8(\text{NO}_2)_2$) in the presence of NaCl salt and employed as a catalyst to accelerate hydrogen production. The hydrogen production rate using ZIF-8 (NaCl) was measured at around $3000 \text{ mL}_{\text{H}_2} \text{ min}^{-1} \text{ g}^{-1}$ [97,99], proving that ZIF-8 exhibited high catalytic activity without any reduction in performance after several cycles in the presence of NaBH_4 . In conclusion, ZIFs are exceptional chemical and thermal stable materials to act as catalysts especially ZIF-67 due to its unsaturated metal centre, Co^{2+} .

Drug delivery system

Zinc is an essential micronutrient for human metabolism [100]. The imidazole group is the main functional group that constitutes the amino acid histidine. These combinations are significant for the development of ZIF as a promising biocompatible drug carrier [49]. 6-Mercaptopurine (6-MP) is a cytotoxic drug used to treat acute childhood leukaemia, provide maintenance therapy to prevent concurrent Crohn's disease, and as a treatment drug for autoimmune hepatitis (AH) [101]. ZIF-8 has been identified as a potential biocompatible drug carrier for 6-MP. An *in-situ* synthesis reaction was conducted to encapsulate 6-MP into ZIF-8 in DMSO at room temperature. Two peaks were observed in the UV-visible spectrum, representing ZIF-8 at 216 nm, and another peak at 320 nm which confirmed the presence of 6-MP on ZIF-8. The average particle size of ZIF-8 also increased the encapsulation of 6-MP, as confirmed by SEM analysis (Scheme 4). The drug release works efficiently at pH 5.0 within 10 hours, as the mildly acidic

solution leads to the dissolution of ZIF-8 structure [102–104].

In a recent study, ZIF-8 showed potential in the drug delivery system for benznidazole (BNZ), a well-known drug to treat Chagas disease. The purpose of the encapsulation of BNZ into ZIF-8 is to overcome the low bioavailability and solubility of BNZ drugs in the human body [105]. The BNZ into ZIF-8 system was developed by the ex-situ method by mixing BNZ solution and ZIF-8 in acetone with the equimolar ratio of BNZ and ZIF-8. Encapsulation of benznidazole (BNZ) into the ZIF-8 framework exhibited a similar condition as 6-MP in ZIF-8, achieving 80% of drug release at pH 4.8 after two days. The disintegration of the framework in an acidic solution allowed the movement of the imidazolate linker within the framework and promoted a greater opening of the pore windows of the framework [106]. Consequently, more diffusion of drug molecules can occur in weak acidic solutions (pH 5.0 – 6.0) [107, 108].



Scheme 4. (a) Encapsulation of 6-mercaptopurine (GMP) into the framework, (b) FESEM analysis of ZIF-8, (c) FESEM analysis of GMP@ZIF-8 and (d) Drug release study at pH 5.0 [105]

The hydrophobic curcumin drug (CCM) was encapsulated in a ZIF-8 framework (CCM-ZIF-8), achieving a maximum efficiency of 83.3% within 15

minutes at room temperature [109]. CCM-ZIF-8 also exhibited superior stability in MeOH after 30 days, as evidently shown by the TEM image. A high average

drug release, reaching 88%, was recorded in an acidic pH solution within 72 hours, attributed from the protonation of 2mIM linkers. This protonation led to the disintegration of the coordination bond between the metal centre and 2mIM linkers, resulting in drug release. Cytotoxicity studies were conducted using a MTT assay to assess the activity of CCM-ZIF-8 and free CCM against HeLa cell lines. The study found a strong inhibitory effect on cell growth with CCM-ZIF-8 compared to free CCM at higher concentrations. At $62.5 \mu\text{g mL}^{-1}$, CCM-ZIF-8 achieved a 57% cell death rate, irrespective to free CCM, which induced only 25% cell death [110].

D- α -Tocopherol succinate (α -TOS) has demonstrated significant cytotoxic effects on various cancer cells via the mitochondrial-dependent pathway while having no toxicity effect on other normal tissue. However, α -TOS has hydrophobic properties that limit its clinical applicability. Therefore, a drug delivery system (DDS) was developed by encapsulating α -TOS into a ZIF-8 framework (α -TOS@ZIF-8) through a one-pot synthesis reaction, followed by functionalisation with hyaluronic acid (HA) on the external surface of α -TOS@ZIF-8 [111]. The function of HA on DDS carriers is to enhance drug accumulation via the CD44 pathway towards the tumour region [109]. The formation of HA/ α -TOS@ZIF-8 was confirmed by zeta potential measurements, where the value decreased from 22.1 mV (pure ZIF-8) to -17.9 mV. This negative value indicated that HA was successfully introduced onto the external layer of α -TOS@ZIF-8. The usage of HA/ α -TOS@ZIF-8 has led to significant tumour growth inhibition, as demonstrated in *in vivo* and *in vitro* studies [112,113]. Similar studies were conducted with surface functionalisation using folic acid (FA) to reduce the cardiotoxicity of doxorubicin (DOX). DOX is an anticancer drug that was successfully modified using pH-sensitive linker cis-aconitic anhydride (CAA) to enhance drug loading into ZIF-8, forming CAD@ZIF-8. This was due to the lack of surface functional groups such as carbonyl and carboxyl groups on ZIF-8. CAD@ZIF-8 was functionalised with FA to enhance tumour targeting and avoid premature drug release. *In vivo* study revealed that mice treated with CAD@ZIF-8-FA showed a slight increase in weight and drug

accumulation in the tumour region at 12 and 24 hours. In contrast, mice treated with DOX experienced a slight weight reduction, and the drug was distributed impartially to various body parts. This implies that CAD@ZIF-8-FA can deliver the drug and accumulate at the tumour region, as opposed to simply encapsulating DOX into ZIF-8. The modification of DOX enables specific targeting of tumour sites in the human body [114].

Conclusion

In conclusion, many new synthesised ZIFs have been successfully synthesised since 2008. It is challenging to incorporate more imidazolate linkers into the framework because different imidazolate linkers have varied reactivities in the synthesis reaction. The synthesis of mixed-linker ZIFs is considered as an interesting development of ZIFs because more functionalities can be added in the frameworks and the materials are suitable for a variety of applications. Instead of employing the solvothermal approach to generate known ZIFs, several methods were developed to produce existing ZIFs to reduce the amount of time needed for the reaction and consumption of hazardous solvents. Therefore, the synthesis strategies of ZIFs such as concentration of precursors, reaction time, the choices of metal salts and solvents must be taken into account as these factors will affect the crystallinity, crystal sizes and the stability of the frameworks. ZIFs have received considerable attention and researchers are currently exploring various applications for ZIF materials. The previous applications of ZIFs were summarised and discussed in detail. Imidazolate linkers provide abundant functionalities in the frameworks and the porous of ZIFs hold great potential across a wide range of applications. The functional properties of ZIFs can be tuneable by the incorporation of imidazolate derivatives linkers in a single framework to enhance the efficiency of ZIFs as catalysts, adsorbents and drug carriers.

Acknowledgement

This research was funded by Universiti Putra Malaysia (UPM) under the Putra Group Initiative (GP-IPB/2017/9581002).

References

- Banerjee R., Furukawa H., Britt D., Knobler C., O'Keeffe M., and Yaghi O.M. (2009). Control of pore size and functionality in isorecticular zeolitic imidazolate frameworks and their carbon dioxide selective capture properties. *Journal of the American Chemical Society*, 131: 3875-3877.
- Wang B., Côté A.P., Furukawa H., O'Keeffe M., and Yaghi O.M. (2008). Colossal cages in zeolitic imidazolate frameworks as selective carbon dioxide reservoirs. *Nature*, 453(7192): 207-211.
- Park K.S., Ni Z., Côté A.P., Choi J.Y., Huang R., Uribe-Romo F.J., Chae H.K., O'Keeffe M., and Yaghi O.M. (2006). Exceptional chemical and thermal stability of zeolitic imidazolate frameworks. *Proceedings of the National Academy of Sciences of the United States of America*, 103(27): 10186-91.
- Nguyen N.T.T., Furukawa H., Gándara F., Nguyen H.T., Cordova K.E., and Yaghi O.M. (2014). Selective capture of carbon dioxide under humid conditions by hydrophobic chabazite-type zeolitic imidazolate frameworks. *Angewandte Chemie - International Edition*, 53: 10645-10648.
- Banerjee R., Phan A., Wang B., Knobler C., Furukawa H., O'Keeffe M., and Yaghi O.M. (2008). High-throughput synthesis of zeolitic imidazolate frameworks and application to CO₂ capture. *Science*, 319: 939-944.
- Morris W., Doonan C.J., Furukawa H., Banerjee R., and Yaghi O.M. (2008). Crystals as molecules: Postsynthesis covalent functionalization of zeolitic imidazolate frameworks. *Journal of the American Chemical Society*, 130(38): 12626-12627.
- Lee Y.R., Kim J., and Ahn W.S. (2013). Synthesis of Metal-Organic Frameworks: A Mini Review. *Korean Journal of Chemical Engineering*, 30(9): 1667-1680.
- Yang J., Zhang Y.B., Liu Q., Trickett C.A., Gutiérrez-Puebla E., Monge M.Á., Cong H., Aldossary A., Deng H., and Yaghi O.M. (2017). Principles of designing extra-large pore openings and cages in zeolitic imidazolate frameworks. *Journal of the American Chemical Society*, 139(18): 6448-6455.
- Kamal K., Bustam M.A., Ismail M., Grekov D., Shariff A.M., and Pré P. (2020). Optimization of washing processes in solvothermal synthesis of nickel-based MOF-74. *Materials*, 13(12): 1-10.
- Hasan M.R., Paseta L., Malankowska M., Téllez C., and Coronas J. (2022). Synthesis of ZIF-94 from recycled mother liquors: Study of the influence of its loading on postcombustion CO₂ capture with pebax based mixed matrix membranes. *Advanced Sustainable Systems*, 6(1): 2100317.
- Kenyotha K., Chanapatttharapol K.C., McCloskey S., and Jantaharn P. (2020). Water based synthesis of ZIF-8 assisted by hydrogen bond acceptors and enhancement of CO₂ uptake by solvent assisted ligand exchange, *Crystals*, 10(7): 1-23.
- Wu R., Fan T., Chen J., and Li Y. (2019). Synthetic factors affecting the scalable production of zeolitic imidazolate frameworks. *ACS Sustainable Chemistry and Engineering*, 7(4): 3632-3646.
- Chen B., Yang Z., Zhu Y., and Xia Y. (2014). Zeolitic imidazolate framework materials: recent progress in synthesis and applications. *Journal of Materials Chemistry A*, 2(40): 16811-16831.
- Sankar S.S., Karthick K., Sangeetha K., Karmakar A., Madhu R., and Kundu S. (2021). Current perspectives on 3D ZIFs incorporated with 1D carbon matrices as fibers via electrospinning processes towards electrocatalytic water splitting: A review. *Journal of Materials Chemistry A*, 9(20): 11961-12002.
- Cheong V.F., and Moh P.Y. (2018). Recent advancement in metal-organic framework: synthesis, activation, functionalisation, and bulk production. *Materials Science and Technology*, 34(9): 1025-1045.
- Hu L., Chen L., Fang Y., Wang A., Chen C., and Yan Z. (2018). Facile synthesis of zeolitic imidazolate framework-8 (ZIF-8) by forming imidazole-based deep eutectic solvent. *Microporous and Mesoporous Materials*, 268: 207-215.
- Wang Y., Xu Y., Li D., Liu H., Li X., Tao S., and Tian Z. (2015). Ionothermal synthesis of zeolitic imidazolate frameworks and the synthesis dissolution-crystallization mechanism, *Chinese Journal of Catalysis*, 36(6): 855-865.
- Gangu K.K., Maddila S., Mukkamala S.B., and

- Jonnalagadda S.B. (2016). A review on contemporary Metal-Organic Framework materials. *Inorganica Chimica Acta*, 446: 61-74.
19. Wang Q., Sun Y., Li S., Zhang P., and Yao Q. (2020). Synthesis and modification of ZIF-8 and its application in drug delivery and tumor therapy. *RSC Advances*, 10(62): 37600-37620.
20. Xiao T., and Liu D. (2019). Progress in the synthesis, properties and applications of ZIF-7 and its derivatives. *Materials Today Energy*, 14(3): 100357.
21. Lucero J.M., Self T.J., and Carreon M.A. (2020). Synthesis of ZIF-11 crystals by microwave heating. *New Journal of Chemistry*, 44(9): 3562-3565.
22. Tran T. Van, Nguyen H., Le P.H.A., Nguyen D.T.C., Nguyen T.T., Nguyen C. Van, Vo D.V.N., and Nguyen T.D. (2020). Microwave-assisted solvothermal fabrication of hybrid zeolitic-imidazolate framework (ZIF-8) for optimizing dyes adsorption efficiency using response surface methodology. *Journal of Environmental Chemical Engineering*, 8(4): 104189.
23. Hayati P., Rezvani A.R., Morsali A., Molina D.R., Geravand S., Suarez-Garcia S., Villaecija M.A.M., García-Granda S., Mendoza-Meroño R., and Retailleau P. (2017). Sonochemical synthesis, characterization, and effects of temperature, power ultrasound and reaction time on the morphological properties of two new nanostructured mercury(II) coordination supramolecule compounds. *Ultrasonics Sonochemistry*, 37: 382-393.
24. Kukkar P., Kim K.H., Kukkar D., and Singh P. (2021). Recent advances in the synthesis techniques for zeolitic imidazolate frameworks and their sensing applications. *Coordination Chemistry Reviews*, 446: 214109.
25. Nalesso S., Varlet G., Bussemaker M.J., Sear R.P., Hodnett M., Monteagudo-Oliván R., Sebastián V., Coronas J., and Lee J. (2021). Sonocrystallisation of ZIF-8 in water with high excess of ligand: Effects of frequency, power and sonication time. *Ultrasonics Sonochemistry*, 76: 105616.
26. Abuzalat O., Wong D., Elsayed M., Park S., and Kim S. (2018). Sonochemical fabrication of Cu(II) and Zn(II) metal-organic framework films on metal substrates, *Ultrasonics Sonochemistry*, 45: 180-188.
27. Jiang S., Shi X., Zu Y., Sun F., and Zhu G. (2021). Interfacial growth of 2D MOF membranes Via contra-diffusion for CO₂ separation. *Materials Chemistry Frontiers*, 5(13): 5150-5157.
28. Long X., Chen Y.S., Zheng Q., Xie X.X., Tang H., Jiang L.P., Jiang J.T., and Qiu J.H. (2020). Removal of iodine from aqueous solution by PVDF/ZIF-8 nanocomposite membranes. *Separation and Purification Technology*, 238: 116488.
29. Karimi A., Vatanpour V., Khataee A., and Safarpour M. (2019). Contra-diffusion synthesis of ZIF-8 layer on polyvinylidene fluoride ultrafiltration membranes for improved water purification. *Journal of Industrial and Engineering Chemistry*, 73: 95-105.
30. Tanaka S., Nagaoka T., Yasuyoshi A., Hasegawa Y., and Denayer J.F.M. (2018). Hierarchical pore development of ZIF-8 MOF by simple salt-assisted mechanosynthesis. *Crystal Growth and Design*, 18(1): 274-279.
31. Thorne M.F., Gómez M.L.R., Bumstead A.M., Li S., and Bennett T.D. (2020). Mechanochemical synthesis of mixed metal, mixed linker glass-forming metal-organic frameworks. *Green Chemistry*, 22(8): 2505-2512.
32. Desai A. V., Sharma S., Let S., and Ghosh S.K. (2019). N-donor linker based metal-organic frameworks (MOFs): Advancement and prospects as functional materials. *Coordination Chemistry Reviews*, 395: 146-192.
33. Utpalla P., Mor J., Sharma S.K., Bahadur J., and Pujari P.K. (2022). Pore interconnectivity and surface accessibility in stiffened mixed linker MOFs: An investigation using variable energy positron spectroscopy, *Journal of Solid State Chemistry*, 307: 122738.
34. Ding R., Zheng W., Yang K., Dai Y., Ruan X., Yan X., and He G. (2020). Amino-functional ZIF-8 nanocrystals by microemulsion based mixed linker strategy and the enhanced CO₂/N₂ separation. *Separation and Purification Technology*, 236: 116209.
35. Eddaoudi M., Kim J., Rosi N., Vodak D., Wachter J., O'Keeffe M., and Yaghi O.M. (2002). Systematic design of pore size and functionality in

- isoreticular MOFs and their application in methane storage. *Science*, 295 (5554): 469-472.
36. Furukawa H., Go Y.B., Ko N., Park Y.K., Uribe-romo F.J., Kim J., Kee M.O., and Yaghi O.M. (2011). Isoreticular expansion of metal-organic frameworks with triangular and square building units and the lowest calculated density for porous crystals. *Inorganic Chemistry*, 50: 9147-9152.
37. Gotzias A. (2017). The effect of gme topology on multicomponent adsorption in zeolitic imidazolate frameworks. *Physical Chemistry Chemical Physics*, 19(1): 871-877.
38. Reif B., Fabisch F., Hovestadt M., Hartmann M., and Schwieger W. (2017). Synthesis of ZIF-11 - Effect of water residues in the solvent onto the phase transition from ZIF-11 to ZIF-7-III. *Microporous and Mesoporous Materials*, 243(3):65-68.
39. Pimentel B.R., Parulkar A., Zhou E.K., Brunelli N.A., and Lively R.P. (2014). Zeolitic imidazolate frameworks: Next-generation materials for energy-efficient gas separations. *ChemSusChem*, 7(12): 3202-3240.
40. Reif B., Paula C., Fabisch F., Hartmann M., Kaspereit M., and Schwieger W. (2019). Synthesis of ZIF-11 – Influence of the synthesis parameters on the phase purity. *Microporous and Mesoporous Materials*, 275 (7):102-110.
41. Feng X., Wu T., and Carreon M.A. (2016). Synthesis of ZIF-67 and ZIF-8 crystals using DMSO (Dimethyl Sulfoxide) as solvent and kinetic transformation studies. *Journal of Crystal Growth*, 455(10): 152-156.
42. Lively R.P., Dose M.E., Thompson J.A., McCool B.A., Chance R.R., and Koros W.J. (2011). Ethanol and water adsorption in methanol-derived ZIF-71. *Chemical Communications*, 47(30): 8667-8669.
43. Fu F., Zheng B., Xie L.H., Du H., Du S., and Dong Z. (2018). Size-controllable synthesis of zeolitic imidazolate framework/carbon nanotube composites. *Crystals*, 8(10): 1-12.
44. Zhang Y., Jia Y., Li M., and Hou L. (2018). Influence of the 2-methylimidazole/zinc nitrate hexahydrate molar ratio on the synthesis of zeolitic imidazolate framework-8 crystals at room temperature. *Scientific Reports*, 8(1): 1-7.
45. Kida K., Okita M., Fujita K., Tanaka S., and Miyake Y. (2013). Formation of high crystalline ZIF-8 in an aqueous solution. *CrystEngComm*, 15(9): 1794-1801.
46. Shi Z., Yu Y., Fu C., Wang L., and Li X. (2017). Water-based synthesis of zeolitic imidazolate framework-8 for CO₂ capture, *RSC Advances*, 7(46): 29227-29232.
47. Jian M., Liu B., Liu R., Qu J., Wang H., and Zhang X. (2015). Water-based synthesis of zeolitic imidazolate framework-8 with high morphology level at room temperature. *RSC Advances*, 5(60): 48433-48441.
48. Lai L.S., Yeong Y.F., Lau K.K., and Shariff A.M. (2016). Effect of synthesis parameters on the formation of ZIF-8 under microwave-assisted solvothermal. *Procedia Engineering*, 148: 35-42.
49. Abdelhamid H.N., Huang Z., El-Zohry A.M., Zheng H., and Zou X. (2017). A fast and scalable approach for synthesis of hierarchical porous zeolitic imidazolate frameworks and one-pot encapsulation of target molecules, *Inorganic Chemistry*, 56(15): 9139-9146.
50. Gross A.F., Sherman E., and Vajo J.J. (2012). Aqueous room temperature synthesis of cobalt and zinc sodalite zeolitic imidazolate frameworks, *Dalton Transactions*, 41(18): 5458-5460.
51. Cravillon J., Nayuk R., Springer S., Feldhoff A., Huber K., and Wiebcke M. (2011). Controlling zeolitic imidazolate framework nano- and microcrystal formation: Insight into crystal growth by time-resolved in situ static light scattering, *Chemistry of Materials*, 23(8): 2130-2141.
52. Ebrahimi A., and Mansournia M. (2017). Cost-effective fabrication of thermal- and chemical-stable ZIF-9 nanocrystals at ammonia atmosphere, *Journal of Physics and Chemistry of Solids*, 111: 12-17.
53. Li Y., Zhou K., He M., and Yao J. (2016). Synthesis of ZIF-8 and ZIF-67 using mixed-base and their dye adsorption, *Microporous and Mesoporous Materials*, 234: 287-292.
54. Huang X.C., Lin Y.Y., Zhang J.P., and Chen X.M. (2006). Ligand-directed strategy for zeolite-type metal-organic frameworks: Zinc(II) imidazoles with unusual zeolitic topologies, *Angewandte*

- Chemie - International Edition*, 45(10): 1557-1559.
55. Zheng W., Ding R., Yang K., Dai Y., Yan X., and He G. (2019). ZIF-8 nanoparticles with tunable size for enhanced CO₂ capture of Pebax based MMMs. *Separation and Purification Technology*, 214: 111-119.
 56. Cravillon J., Schröder C.A., Bux H., Rothkirch A., Caro J., and Wiebcke M. (2012). Formate modulated solvothermal synthesis of ZIF-8 investigated using time-resolved in situ X-ray diffraction and scanning electron microscopy. *CrystEngComm*, 14(2): 492-498.
 57. Seoane B., Castellanos S., Dikhtiarenko A., Kapteijn F., and Gascon J. (2016). Multi-scale crystal engineering of metal organic frameworks. *Coordination Chemistry Reviews*, 307: 147-187.
 58. Oozeerally R., Ramkhalawan S.D.K., Burnett D.L., Tempelman C.H.L., and Degirmenci V. (2019). ZIF-8 metal organic framework for the conversion of glucose to fructose and 5-hydroxymethyl furfural, *Catalysts*, 9(812): 1-14.
 59. Zhao X., Fang X., Wu B., Zheng L., and Zheng N. (2014). Facile synthesis of size-tunable ZIF-8 nanocrystals using reverse micelles as nanoreactors, *Science China Chemistry*, 57(1): 141-146.
 60. Cheetham A.K., Kieslich G., and Yeung H.H.M. (2018). Thermodynamic and kinetic effects in the crystallization of metal-organic frameworks. *Accounts of Chemical Research*, 51(3): 659-667.
 61. Ta D.N., Nguyen H.K.D., Trinh B.X., Le Q.T.N., Ta H.N., and Nguyen H.T. (2018). Preparation of nano-ZIF-8 in methanol with high yield. *Canadian Journal of Chemical Engineering*, 96(7): 1518-1531.
 62. Tsai C.W., and Langner E.H.G. (2016). The effect of synthesis temperature on the particle size of nano-ZIF-8, *Microporous and Mesoporous Materials*, 221: 8-13.
 63. Feng Y., Li Y., Xu M., Liu S., and Yao J. (2016). Fast adsorption of methyl blue on zeolitic imidazolate framework-8 and its adsorption mechanism, *RSC Advances*, 6(111): 109608-109612.
 64. Luan Tran B., Chin H.Y., Chang B.K., and Chiang A.S.T. (2019). Dye adsorption in ZIF-8: The importance of external surface area. *Microporous and Mesoporous Materials*, 277: 149-153.
 65. Fan X., Wang W., Li W., Zhou J., Wang B., Zheng J., and Li X. (2014). Highly porous ZIF-8 nanocrystals prepared by a surfactant mediated method in aqueous solution with enhanced adsorption kinetics. *ACS Applied Materials and Interfaces*, 17: 14994-14999.
 66. Fernandez-Perez A., and Marban G. (2020). Visible light spectroscopic analysis of methylene blue in water; what comes after dimer? *ACS Omega*, 5(46): 29801-29815.
 67. Heydari Moghaddam M., Nabizadeh R., Dehghani M.H., Akbarpour B., Azari A., and Yousefi M. (2019). Performance investigation of Zeolitic Imidazolate Framework – 8 (ZIF-8) in the removal of trichloroethylene from aqueous solutions. *Microchemical Journal*, 150: 104185.
 68. Saracco G., Vankova S., Pagliano C., Bonelli B., and Garrone E. (2014). Outer Co(II) ions in Co-ZIF-67 reversibly adsorb oxygen from both gas phase and liquid water. *Physical Chemistry Chemical Physics*, 16 (13): 6139-6145.
 69. Tu N.T.T., Thien T.V., Du P.D., Thanh Chau V.T., Mau T.X., and Khieu D.Q. (2018). Adsorptive removal of Congo red from aqueous solution using zeolitic imidazolate framework-67. *Journal of Environmental Chemical Engineering*, 6(2): 2269-2280.
 70. Lin K.Y.A., and Chang H.A. (2015). Ultra-high adsorption capacity of zeolitic imidazole framework-67 (ZIF-67) for removal of malachite green from water. *Chemosphere*, 139: 624-631.
 71. Bekçi Z., Özveri C., Seki Y., and Yurdakoç K. (2008). Sorption of malachite green on chitosan bead. *Journal of Hazardous Materials*, 154: 254-261.
 72. Huo S.H., and Yan X.P. (2012). Metal-organic framework MIL-100(Fe) for the adsorption of malachite green from aqueous solution, *Journal of Materials Chemistry*, 22(15): 7449-7455.
 73. Liao S.-M., Du Q.-S., Meng J.-Z., Pang Z.-W., and Huang R.-B. (2013). Evidence for a functionally important histidine residue in human tyrosine hydroxylase, *Chemistry Central Journal*, 7(44): 1-12.
 74. Yu R., and Wu Z. (2020). High adsorption for

- ofloxacin and reusability by the use of ZIF-8 for wastewater treatment. *Microporous and Mesoporous Materials*, 308 (3): 110494.
75. Daghrir R., and Drogui P. (2013). Tetracycline antibiotics in the environment: A review. *Environmental Chemistry Letters*, 11(3): 209-227.
76. Golet E.M., Alder A.C., and Giger W. (2002). Environmental exposure and risk assessment of fluoroquinolone antibacterial agents in wastewater and river water of the Glatt Valley watershed, Switzerland. *Environmental Science and Technology*, 36(17): 3645-3651.
77. Zhou L., Li N., Owens G., and Chen Z. (2019). Simultaneous removal of mixed contaminants, copper and norfloxacin, from aqueous solution by ZIF-8. *Chemical Engineering Journal*, 362: 628-637.
78. Wu C.S., Xiong Z.H., Li C., and Zhang J.M. (2015). Zeolitic imidazolate metal organic framework ZIF-8 with ultra-high adsorption capacity bound tetracycline in aqueous solution. *RSC Advances*, 5(100): 82127-82137.
79. Xiang Y., Yang X., Xu Z., Hu W., Zhou Y., Wan Z., Yang Y., Wei Y., Yang J., and Tsang D.C.W. (2020). Fabrication of sustainable manganese ferrite modified biochar from vinasse for enhanced adsorption of fluoroquinolone antibiotics: Effects and mechanisms. *Science of the Total Environment*, 709: 136079.
80. Li N., Zhou L., Jin X., Owens G., and Chen Z. (2018). Simultaneous removal of tetracycline and oxytetracycline antibiotics from wastewater using a ZIF-8 metal organic-framework. *Journal of Hazardous Materials*, 366: 563-572.
81. Petkovic H., Lukežić T., and Šušković J. (2017). Biosynthesis of oxytetracycline by *streptomyces rimosus*: Past, present and future directions in the development of tetracycline antibiotics. *Food Technology and Biotechnology*, 55(1): 3-13.
82. Ocampo-Pérez R., Rivera-Utrilla J., Gómez-Pacheco C., Sánchez-Polo M., and López-Peñalver J.J. (2012). Kinetic study of tetracycline adsorption on sludge-derived adsorbents in aqueous phase. *Chemical Engineering Journal*, 213: 88-96.
83. Enayati M., Gong Y., and Abbaspourrad A. (2019). Synthesis of lactose lauryl ester in organic solvents using aluminosilicate zeolite as a catalyst. *Food Chemistry*, 279: 401-407.
84. Sarmah B., Satpati B., and Srivastava R. (2017). Highly efficient and recyclable basic mesoporous zeolite catalyzed condensation, hydroxylation, and cycloaddition reactions. *Journal of Colloid and Interface Science*, 493: 307-316.
85. Shalaby N.H., Elsalamony R.A., and El Naggar A.M.A. (2018). Mesoporous waste-extracted SiO₂-Al₂O₃-supported Ni and Ni-H₃PW₁₂O₄₀ nano-catalysts for photo-degradation of methyl orange dye under UV irradiation. *New Journal of Chemistry*, 42(11): 9177-9186.
86. Terrade F.G., van Krieken J., Verkuil B.J.V., and Bouwman E. (2017). Catalytic cracking of lactide and poly(lactic acid) to acrylic acid at low temperatures. *ChemSusChem*, 10(9): 1904-1908.
87. VanWouwe P., Dusselier M., Vanleeuw E., and Sels B. (2016). Lactide synthesis and chirality control for polylactic acid production, *ChemSusChem*, 9(9): 907-921.
88. Kricheldorf H.R. (2001). Syntheses and application of polylactides. *Chemosphere*, 43(1): 49-54.
89. Luo Z., Chaemchuen S., Zhou K., and Verpoort F. (2017). Ring-opening polymerization of L-lactide to cyclicpoly(lactide) by zeolitic imidazole framework ZIF-8 catalyst. *ChemSusChem*, 10(21): 4135-4139.
90. Aresta M., Dibenedetto A., and Angelini A. (2014). Catalysis for the valorization of exhaust carbon: from CO₂ to chemicals, materials and fuels. Technological use of CO₂. *Encyclopedia of Inorganic and Bioinorganic Chemistry*, 3: 1709-1742.
91. Bhin K.M., Tharun J., Roshan K.R., Kim D., Chung Y., and Park D. (2017). Catalytic performance of zeolitic imidazolate framework ZIF-95 for the solventless synthesis of cyclic carbonates from CO₂ and epoxides. *Journal of CO₂ Utilization*, 17: 112-118.
92. Jose T., Hwang Y., Kim D.W., Kim M. Il, and Park D.W. (2015). Functionalized zeolitic imidazolate framework F-ZIF-90 as efficient catalyst for the cycloaddition of carbon dioxide to allyl glycidyl ether, *Catalysis Today*, 245: 61-67.
93. Ivanchikova I.D., Evtushok V.Y., Zalomaeva O. V., Kolokolov D.I., Stepanov A.G., and Kholdeeva O.A.

- (2020). Heterogeneous epoxidation of menadione with hydrogen peroxide over the zeolite imidazolate framework ZIF-8. *Dalton Transactions*, 49(36): 12546-12549.
94. Chin M., Cisneros C., Araiza S.M., Vargas K.M., Ishihara K.M., and Tian F. (2018). Rhodamine B degradation by nanosized zeolitic imidazolate framework-8 (ZIF-8). *RSC Advances*, 8(47): 26987-26997.
95. Wang T., Wang Y., Sun M., Hanif A., Wu H., Gu Q., Ok Y.S., Tsang D.C.W., Li J., Yu J., and Shang J. (2020). Thermally treated zeolitic imidazolate framework-8 (ZIF-8) for visible light photocatalytic degradation of gaseous formaldehyde. *Chemical Science*, 11(26): 6670-6681.
96. Park H., Amaranatha Reddy D., Kim Y., Ma R., Choi J., Kim T.K., and Lee K.S. (2016). Zeolitic imidazolate framework-67 (ZIF-67) rhombic dodecahedrons as full-spectrum light harvesting photocatalyst for environmental remediation. *Solid State Sciences*, 62: 82-89.
97. Wang M., Liu J., Guo C., Gao X., Gong C., Wang Y., Liu B., Li X., Gurzadyan G.G., and Sun L. (2018). Metal-organic frameworks (ZIF-67) as efficient cocatalysts for photocatalytic reduction of CO₂: The role of the morphology effect, *Journal of Materials Chemistry A*, 6: 4768-4775.
98. White J.L., Baruch M.F., Pander J.E., Hu Y., Fortmeyer I.C., Park J.E., Zhang T., Liao K., Gu J., Yan Y., Shaw T.W., Abelev E., and Bocarsly A.B. (2015). Light-driven heterogeneous reduction of carbon dioxide: Photocatalysts and photoelectrodes. *Chemical Reviews*, 115(23): 12888-12935.
99. Pattengale B., Santalucia D.J., Yang S., Hu W., Liu C., Zhang X., Berry J.F., and Huang J. (2018). Direct observation of node-to-node communication in zeolitic imidazolate frameworks, *Journal of the American Chemical Society*, 140(37): 11573-11576.
100. Saper R.B., and Rash R. (2009). Zinc: An essential micronutrient. *American Family Physician*, 79(9): 768-772.
101. Karagiari O., Lalonde M.B., Bury W., Sarjeant A.A., Farha O.K., and Hupp J.T. (2012). Opening ZIF-8: A catalytically active zeolitic imidazolate framework of sodalite topology with unsubstituted linkers, *Journal of the American Chemical Society*, 134(45): 18790-18796.
102. Aarbakke J., Janka-Schaub G., and Elion G.B. (1997). Thiopurine biology and pharmacology. *Trends in Pharmacological Sciences*, 18(1): 3-7.
103. Hanauer S.B., Korelitz B.I., Rutgeerts P., Peppercorn M.A., Thisted R.A., Cohen R.D., and Present D.H. (2004). Postoperative maintenance of Crohn's disease remission with 6-mercaptopurine, mesalamine, or placebo: A 2-year trial, *Gastroenterology*, 127(3): 723-729.
104. Hübener S., Oo Y.H., Than N.N., Hübener P., Weiler-Normann C., Lohse A.W., and Schramm C. (2016). Efficacy of 6-mercaptopurine as second-line treatment for patients with autoimmune hepatitis and azathioprine intolerance. *Clinical Gastroenterology and Hepatology*, 14(3): 445-453.
105. Kaur H., Mohanta G.C., Gupta V., Kukkar D., and Tyagi S. (2017). Synthesis and characterization of ZIF-8 nanoparticles for controlled release of 6-mercaptopurine drug. *Journal of Drug Delivery Science and Technology*, 41: 106-112.
106. Müller Kratz J., Garcia Bournissen F., Forsyth C.J., and Sosa-Estani S. (2018). Clinical and pharmacological profile of benznidazole for treatment of chagas disease. Taylor & Francis.
107. Coudert F.X. (2017). Molecular mechanism of swing effect in zeolitic imidazolate framework ZIF-8: Continuous deformation upon adsorption. *ChemPhysChem*, 18(19): 2732-2738.
108. Xia Y., Hong Y., Geng R., Li X., Qu A., Zhou Z., and Zhang Z. (2020). Amine-functionalized ZIF-8 as a fluorescent probe for breath volatile organic compound biomarker detection of lung cancer patients. *ACS Omega*, 5(7): 3478-3486.
109. Tiwari A., Singh A., Garg N., and Randhawa J.K. (2017). Curcumin encapsulated zeolitic imidazolate frameworks as stimuli responsive drug delivery system and their interaction with biomimetic environment. *Scientific Reports*, 7(1): 1-12.
110. Moura Ferraz L.R. de, Tabosa A.É.G.A., da Silva Nascimento D.D.S., Ferreira A.S., de Albuquerque Wanderley Sales V., Silva J.Y.R., Júnior S.A., Rolim L.A., de Souza Pereira J.J., and Rolim-Neto P.J. (2020). ZIF-8 as a promising drug delivery system for benznidazole: development, characterization, in vitro dialysis release and

- cytotoxicity. *Scientific Reports*, 10(1): 1-14.
111. Sun Q., Bi H., Wang Z., Li C., Wang X., Xu J., Zhu H., Zhao R., He F., Gai S., and Yang P. (2019). Biomaterials hyaluronic acid-targeted and pH-responsive drug delivery system based on metal-organic frameworks for efficient antitumor therapy. *Biomaterials*, 223: 119473.
 112. Lin C.W., Lu K.Y., Wang S.Y., Sung H.W., and Mi F.L. (2016). CD44-specific nanoparticles for redox-triggered reactive oxygen species production and doxorubicin release. *Acta Biomaterialia*, 35: 280-292.
 113. Song L., Pan Z., Zhang H., Li Y., Zhang Y., Lin J., Su G., Ye S., Xie L., Li Y., and Hou Z. (2017). Dually folate/CD44 receptor-targeted self-assembled hyaluronic acid nanoparticles for dual-drug delivery and combination cancer therapy. *Journal of Materials Chemistry B*, 5(33): 6835-6846.
 114. Yan J., Liu C., Wu Q., Zhou J., Xu X., Zhang L., Wang D., Yang F., and Zhang H. (2020). Mineralization of pH-sensitive doxorubicin prodrug in ZIF-8 to enable targeted delivery to solid tumors. *Analytical Chemistry*, 92(16): 11453-11461.