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Development of Metal–Organic Framework-Based Nanocomposites for Selective Gas Separation and Carbon Capture Applications

DR L MAHESWARA REDDY

Academic Consultant, Department of Science and Humanities,
Y.S.R. Engineering College of YVU, Proddatur - 516360
Mail id: lebakamaheswarareddy@gmail.com

ABSTRACT: *The rapid increase in greenhouse gas emissions resulting from industrialization, fossil fuel combustion, and energy-intensive manufacturing processes has intensified global concerns regarding climate change and environmental sustainability. Carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) constitute the primary greenhouse gases responsible for global warming and atmospheric pollution. Conventional gas separation technologies, including cryogenic distillation, pressure swing adsorption, membrane separation, and chemical absorption using amine solutions, often suffer from high energy consumption, limited selectivity, solvent degradation, corrosion, and substantial operational costs. Consequently, there is an urgent need for advanced porous materials capable of achieving highly efficient, selective, and energy-efficient gas separation and carbon capture. Metal–Organic Frameworks (MOFs), characterized by exceptionally high surface area, tunable pore structures, adjustable chemical functionality, and excellent adsorption properties, have emerged as one of the most promising classes of porous materials for next-generation gas separation technologies. Nevertheless, the practical implementation of pristine MOFs is often limited by inadequate mechanical stability, moisture sensitivity, and processing challenges. The development of MOF-based nanocomposites through the incorporation of nanoparticles, polymers, carbon nanomaterials, and inorganic supports significantly enhances structural stability, adsorption capacity, selectivity, and long-term operational performance. This research focuses on the synthesis, characterization, and performance evaluation of MOF-based nanocomposites for selective gas separation and carbon capture applications. The synthesized nanocomposites are characterized using X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Brunauer–Emmett–Teller (BET) surface area analysis, Thermogravimetric Analysis (TGA), and gas adsorption measurements. Experimental investigations demonstrate that the developed MOF nanocomposites exhibit significantly enhanced CO_2 adsorption capacity, excellent CO_2/N_2 and CO_2/CH_4 selectivity, superior thermal stability, and outstanding cyclic regeneration performance compared with conventional adsorbent materials. The proposed nanocomposite system provides an efficient, sustainable, and economically attractive solution for industrial carbon capture, natural gas purification, hydrogen production, and environmental pollution control.*

INTRODUCTION

The unprecedented growth of industrial activities, urbanization, transportation, and fossil fuel utilization has resulted in a continuous increase in atmospheric greenhouse gas concentrations, leading to severe environmental consequences including global warming, climate change, ocean acidification, and ecosystem degradation. Carbon dioxide contributes the largest proportion of anthropogenic greenhouse gas emissions, primarily originating from coal-fired power plants, cement manufacturing, petroleum refining, steel production, chemical processing industries, and transportation systems. The increasing concentration of atmospheric CO_2 has intensified international efforts toward developing efficient carbon capture,

utilization, and storage (CCUS) technologies capable of mitigating greenhouse gas emissions while supporting sustainable industrial development.

Gas separation processes are fundamental operations in numerous industrial sectors, including natural gas purification, hydrogen production, oxygen enrichment, biogas upgrading, carbon capture, air separation, petrochemical manufacturing, and environmental pollution control. Conventional gas separation techniques such as cryogenic distillation, chemical absorption, membrane filtration, and pressure swing adsorption have been extensively employed for industrial gas purification. Although these technologies provide acceptable separation efficiencies, they frequently require substantial energy input, expensive infrastructure, continuous solvent regeneration, and high maintenance costs. Furthermore, chemical absorbents such as monoethanolamine suffer from solvent degradation, corrosion, toxicity, and considerable energy penalties during regeneration, thereby limiting their long-term sustainability.

Porous solid adsorbents have emerged as attractive alternatives because of their low energy requirements, high regeneration capability, and improved operational efficiency. Activated carbon, zeolites, porous silica, and carbon molecular sieves have traditionally been employed for adsorption-based gas separation. However, these materials generally possess limited pore tunability and restricted adsorption selectivity toward specific gas molecules. Consequently, researchers have focused on developing advanced nanoporous materials capable of providing precisely controlled pore structures, exceptionally high surface areas, and chemically functionalized adsorption sites.

Metal–Organic Frameworks (MOFs) represent one of the most important classes of crystalline porous materials developed during the past two decades. MOFs consist of metal ions or metal clusters connected through organic ligands, forming highly ordered three-dimensional porous networks with extremely large internal surface areas. The modular nature of MOF synthesis enables precise control over pore size, pore geometry, chemical functionality, and adsorption characteristics by selecting appropriate metal centers and organic linkers. Numerous MOFs exhibit surface areas exceeding 6000 m^2/g, making them among the most porous materials ever synthesized. Their exceptionally high porosity and tunable adsorption behavior make them highly suitable for selective gas separation, hydrogen storage, methane storage, catalysis, drug delivery, sensing, and environmental remediation.

Several well-known MOFs, including MOF-5, HKUST-1, UiO-66, MIL-101, MIL-53, and ZIF-8, have demonstrated remarkable adsorption performance for carbon dioxide and other industrial gases. Carbon dioxide molecules exhibit strong interactions with functional groups present within MOF pores because of their quadrupole moment and molecular polarity. Functionalization of MOFs using amino groups, hydroxyl groups, fluorinated ligands, or open metal sites further enhances selective CO_2 adsorption through improved electrostatic interactions and chemisorption mechanisms. Nevertheless, pristine MOFs often suffer from limited hydrothermal stability, moisture sensitivity, mechanical fragility, powder handling difficulties, and structural degradation under harsh industrial conditions, restricting their commercial implementation.

To overcome these limitations, significant research efforts have focused on the development of **MOF-based nanocomposites**, in which MOFs are integrated with polymers, carbon nanotubes, graphene oxide, activated carbon, silica nanoparticles, metal oxide nanoparticles, cellulose nanofibers, and ceramic supports. The incorporation of these secondary materials substantially improves mechanical strength, moisture resistance, structural durability, thermal stability, and processability while maintaining the excellent adsorption properties of the parent MOFs. Polymer-supported MOFs facilitate membrane

fabrication for continuous gas separation, whereas graphene oxide and carbon nanotubes improve electrical conductivity, structural reinforcement, and adsorption kinetics. Metal oxide nanoparticles provide additional active adsorption sites and improve chemical stability under humid operating environments.

Comprehensive characterization of MOF nanocomposites is essential for understanding the relationship between synthesis conditions, structural properties, pore characteristics, and adsorption performance. X-ray Diffraction is employed to verify crystalline structure and phase purity, while Fourier Transform Infrared Spectroscopy confirms chemical bonding and functional group interactions between MOFs and nanocomposite components. Scanning Electron Microscopy and Transmission Electron Microscopy reveal particle morphology, crystal size, and dispersion of nanoparticles throughout the composite matrix. Brunauer–Emmett–Teller surface area analysis provides quantitative evaluation of pore size distribution and specific surface area, whereas Thermogravimetric Analysis assesses thermal stability under elevated temperatures. Gas adsorption experiments determine carbon dioxide uptake capacity, adsorption kinetics, regeneration efficiency, and gas selectivity under different operating conditions.

The present research focuses on the development of advanced MOF-based nanocomposites possessing enhanced structural stability, adsorption efficiency, and gas selectivity for carbon capture applications. By combining highly porous MOFs with suitable nanostructured reinforcement materials, the investigation aims to improve adsorption capacity, cyclic stability, mechanical integrity, and industrial applicability. The outcomes of this study are expected to contribute significantly toward the development of sustainable, energy-efficient, and environmentally friendly carbon capture technologies suitable for power generation, chemical processing, natural gas purification, hydrogen production, and greenhouse gas mitigation.

Problem Statement

Conventional gas separation and carbon capture technologies are associated with high energy consumption, low adsorption selectivity, solvent degradation, corrosion, and substantial operational costs. Although Metal–Organic Frameworks exhibit exceptional adsorption capacity and tunable pore structures, their practical implementation is limited by moisture sensitivity, poor mechanical stability, structural degradation, and processing difficulties. Therefore, there is a critical need to develop **MOF-based nanocomposites** possessing enhanced structural stability, superior gas selectivity, high adsorption capacity, excellent regeneration capability, and long-term operational durability for efficient industrial carbon capture and selective gas separation.

Objective

The primary objective of this research is to develop high-performance Metal–Organic Framework-based nanocomposites for selective gas separation and carbon capture applications. The study aims to synthesize structurally stable nanocomposites, investigate their physicochemical properties through comprehensive material characterization, evaluate their adsorption behavior toward carbon dioxide and industrial gases, optimize gas separation performance, and assess regeneration stability under repeated adsorption–desorption cycles. Furthermore, the research seeks to establish correlations between nanocomposite composition, pore structure, adsorption mechanisms, and separation efficiency for sustainable industrial implementation.

Scope

The scope of this research includes the synthesis of MOF-based nanocomposites using advanced porous MOFs combined with polymeric, carbon-based, or inorganic nanomaterials through controlled fabrication techniques. Structural characterization is performed using XRD, FTIR, SEM, TEM, BET surface area analysis, and TGA, while adsorption behavior is evaluated through gas adsorption experiments involving CO_2, N_2, CH_4, and H_2. The investigation examines adsorption capacity, selectivity, adsorption kinetics, regeneration efficiency, thermal stability, pore characteristics, and cyclic performance under simulated industrial conditions. The developed nanocomposites are intended for applications in **carbon capture and storage (CCS), post-combustion CO_2 capture, natural gas purification, hydrogen purification, biogas upgrading, industrial gas separation, environmental pollution control, and sustainable greenhouse gas mitigation technologies**.

LITERATURE SURVEY

The increasing concentration of atmospheric greenhouse gases has intensified worldwide research into advanced gas separation technologies capable of reducing industrial carbon emissions while maintaining energy efficiency and economic feasibility. Carbon dioxide is recognized as the dominant greenhouse gas contributing to global warming because of its extensive release from fossil fuel combustion, power generation, cement production, petrochemical industries, and transportation. Conventional carbon capture methods such as chemical absorption using aqueous amine solutions have been widely implemented due to their relatively high capture efficiency. However, these processes require substantial regeneration energy, suffer from solvent degradation, equipment corrosion, and high operating costs, thereby motivating researchers to investigate alternative adsorption-based separation technologies that provide improved efficiency and sustainability.

Among solid adsorbent materials, activated carbon has historically been one of the most commonly employed materials because of its relatively high surface area, chemical stability, and low production cost. Activated carbon effectively adsorbs various industrial gases through physical adsorption mechanisms, but its limited pore size control and relatively weak interaction with carbon dioxide restrict adsorption selectivity under practical operating conditions. Similarly, zeolites have demonstrated excellent adsorption capacity for carbon dioxide because of their crystalline microporous structure and strong electrostatic interactions with polar gas molecules. Nevertheless, zeolites often experience reduced adsorption performance under humid conditions because water molecules preferentially occupy adsorption sites, thereby decreasing carbon dioxide uptake during industrial operation.

The discovery of **Metal–Organic Frameworks (MOFs)** has revolutionized porous materials research because of their exceptionally high surface area, tunable pore architecture, adjustable chemical functionality, and remarkable adsorption capabilities. MOFs consist of metal ions or metal clusters connected by organic ligands to form highly ordered three-dimensional crystalline frameworks. Their modular synthesis enables precise control over pore size, pore volume, surface chemistry, and adsorption properties by selecting different combinations of metal centers and organic linkers. Numerous investigations have reported surface areas exceeding 5000–7000 m^2/g, making MOFs among the most porous materials available for gas storage and separation applications.

Several commercially important MOFs have been extensively investigated for selective carbon dioxide adsorption. **MOF-5** demonstrated exceptionally high porosity but exhibited relatively poor moisture resistance, limiting industrial implementation. **HKUST-1** showed excellent adsorption capacity resulting

from open copper metal sites that strongly interact with carbon dioxide molecules; however, structural degradation under humid environments reduced long-term operational stability. Zirconium-based frameworks such as **UiO-66** attracted significant attention because of their superior hydrothermal stability, excellent mechanical strength, and resistance to acidic and basic environments. Similarly, **MIL-101**, **MIL-53**, and **ZIF-8** demonstrated remarkable adsorption performance together with tunable pore structures suitable for selective separation of carbon dioxide from nitrogen, methane, and hydrogen mixtures.

To further enhance adsorption selectivity, researchers introduced various chemical functionalization strategies within MOF structures. Amino-functionalized MOFs significantly improved carbon dioxide adsorption because amino groups establish strong acid-base interactions with acidic carbon dioxide molecules. Hydroxyl-functionalized frameworks increased hydrogen bonding interactions, while fluorinated organic ligands enhanced gas selectivity through favorable electrostatic interactions. The incorporation of open metal sites within MOF frameworks also promoted stronger adsorption by providing additional coordination sites for carbon dioxide molecules. These functionalization approaches substantially increased adsorption capacity, particularly under low-pressure conditions relevant to post-combustion carbon capture.

Although pristine MOFs possess exceptional adsorption properties, their practical industrial implementation remains limited by several inherent challenges. Many MOFs exhibit poor mechanical strength, making them susceptible to structural collapse during pelletization and industrial processing. Moisture sensitivity represents another significant limitation because exposure to humid gas streams frequently causes framework degradation and reduced adsorption capacity. Additionally, the powdered nature of most synthesized MOFs complicates handling, reactor packing, membrane fabrication, and continuous industrial operation. These limitations have encouraged extensive investigation into **MOF-based nanocomposites**, which combine MOFs with complementary nanomaterials to improve structural stability and processing characteristics.

Polymer-supported MOF nanocomposites have emerged as one of the most promising solutions for industrial gas separation. Polymers such as polyimide, polysulfone, polyethersulfone, polyvinylidene fluoride, and cellulose acetate have been employed as supporting matrices for MOF particles. These mixed-matrix membranes combine the excellent gas selectivity of MOFs with the flexibility, durability, and processability of polymers. Numerous studies have demonstrated that polymer-supported MOF membranes exhibit significantly improved mechanical strength, reduced defect formation, enhanced permeability, and stable long-term gas separation performance compared with pure polymer membranes.

Carbon nanomaterials including graphene oxide, carbon nanotubes, activated carbon, and carbon nanofibers have also been incorporated into MOFs to produce multifunctional nanocomposites with enhanced adsorption properties. Graphene oxide provides additional adsorption sites, improves structural reinforcement, facilitates electron transport, and increases moisture resistance. Carbon nanotubes enhance mechanical strength and create interconnected diffusion pathways that accelerate gas transport through composite materials. These synergistic interactions improve adsorption kinetics while preserving the high porosity characteristic of MOF structures.

Recent research has also explored the incorporation of inorganic nanoparticles such as titanium dioxide, zinc oxide, silica, alumina, and magnetic iron oxide into MOF matrices. These nanoparticles improve hydrothermal stability, increase structural rigidity, and provide additional active adsorption sites for

selective gas separation. Magnetic MOF nanocomposites offer the additional advantage of simple magnetic recovery following adsorption processes, making them particularly attractive for large-scale environmental remediation and industrial carbon capture systems.

Comprehensive characterization techniques have become indispensable for evaluating the structural and functional properties of MOF nanocomposites. X-ray Diffraction confirms crystal structure preservation following nanocomposite synthesis, whereas Fourier Transform Infrared Spectroscopy verifies chemical interactions between MOFs and secondary materials. Scanning Electron Microscopy and Transmission Electron Microscopy provide detailed information regarding particle morphology, crystal size, pore distribution, and nanomaterial dispersion. Brunauer–Emmett–Teller surface area analysis determines specific surface area, pore volume, and pore size distribution, while Thermogravimetric Analysis evaluates thermal stability under elevated operating temperatures. Gas adsorption experiments employing carbon dioxide, nitrogen, methane, and hydrogen enable quantitative assessment of adsorption capacity, adsorption kinetics, regeneration efficiency, and gas selectivity.

Despite remarkable progress in MOF-based nanocomposite development, several important challenges remain before widespread industrial commercialization can be achieved. Large-scale synthesis methods require further optimization to reduce production costs while maintaining structural uniformity and reproducibility. Long-term stability under humid industrial environments, resistance to repeated adsorption–desorption cycling, scalable membrane fabrication, and integration into continuous industrial gas separation systems continue to require significant investigation. Furthermore, balancing adsorption capacity, selectivity, regeneration efficiency, mechanical durability, and economic feasibility remains a major research challenge.

The present research addresses these challenges through the **development of advanced Metal–Organic Framework-based nanocomposites** possessing enhanced structural stability, superior adsorption performance, and excellent regeneration capability. Comprehensive structural, morphological, thermal, and adsorption characterization is performed to establish clear relationships between nanocomposite composition, pore architecture, surface functionality, gas adsorption mechanisms, and separation efficiency. The outcomes of this investigation are expected to contribute significantly toward the development of sustainable, energy-efficient, and environmentally friendly materials for **industrial carbon capture, greenhouse gas mitigation, natural gas purification, hydrogen production, and next-generation selective gas separation technologies**.

METHODOLOGY

The present research proposes a systematic methodology for the **development, synthesis, characterization, and performance evaluation of Metal–Organic Framework (MOF)-based nanocomposites** for selective gas separation and carbon capture applications. The methodology integrates MOF synthesis, nanocomposite fabrication, structural characterization, pore analysis, adsorption studies, gas separation evaluation, regeneration testing, and performance validation to develop highly efficient porous adsorbents with enhanced adsorption capacity, excellent gas selectivity, superior thermal stability, and long-term cyclic durability. The experimental workflow consists of precursor selection, MOF synthesis, nanocomposite preparation, physicochemical characterization, gas adsorption measurements, selectivity analysis, regeneration studies, and comparative performance evaluation.

Initially, suitable metal precursors and organic linkers were selected to synthesize a highly porous Metal–Organic Framework. Zinc nitrate hexahydrate was selected as the metal source, while 2-methylimidazole served as the organic ligand for the preparation of ZIF-8 owing to its excellent chemical stability and high carbon dioxide adsorption capability. Both precursors were separately dissolved in methanol under continuous magnetic stirring until homogeneous solutions were obtained. The ligand solution was gradually introduced into the metal precursor solution under controlled stirring conditions, allowing nucleation and crystal growth to occur uniformly. The reaction mixture was maintained at room temperature for several hours to ensure complete formation of highly crystalline MOF particles.

Following MOF synthesis, the resulting crystals were collected through centrifugation, repeatedly washed with methanol to remove unreacted precursors, and dried under vacuum. To improve structural stability and adsorption performance, graphene oxide nanoparticles were incorporated into the synthesized MOF through ultrasonic dispersion followed by solution mixing. The graphene oxide sheets acted as reinforcing nanostructures that enhanced mechanical strength, increased accessible adsorption sites, and improved electron transfer pathways. Continuous stirring and ultrasonication ensured homogeneous dispersion of graphene oxide throughout the MOF framework without significant particle agglomeration.

The synthesized MOF–graphene oxide nanocomposite was further subjected to mild thermal activation under vacuum to eliminate trapped solvent molecules and fully activate the porous structure. Controlled activation preserved the crystalline framework while exposing internal adsorption sites necessary for efficient gas capture. The activated nanocomposite powder was subsequently pelletized under moderate pressure to obtain mechanically stable samples suitable for gas adsorption experiments and industrial handling.

Comprehensive structural characterization was performed to investigate the physicochemical properties of the synthesized nanocomposite. X-ray Diffraction (XRD) analysis confirmed the preservation of the crystalline MOF framework after graphene oxide incorporation by comparing diffraction peaks with standard reference patterns. Fourier Transform Infrared Spectroscopy (FTIR) was employed to identify characteristic functional groups and verify chemical interactions between the MOF structure and graphene oxide nanosheets. Scanning Electron Microscopy (SEM) provided detailed information regarding particle morphology, crystal distribution, and surface homogeneity, while Transmission Electron Microscopy (TEM) examined the nanoscale dispersion of graphene oxide within the porous framework.

Surface area and pore characteristics were investigated using Brunauer–Emmett–Teller (BET) nitrogen adsorption analysis. Specific surface area, total pore volume, and pore size distribution were determined to evaluate the availability of adsorption sites for gas molecules. Thermogravimetric Analysis (TGA) was subsequently performed to assess thermal stability by monitoring weight loss under controlled heating conditions. The obtained thermal decomposition profile established the operational temperature range suitable for industrial gas separation applications.

Gas adsorption performance was evaluated using a high-pressure volumetric adsorption system. Pure carbon dioxide, nitrogen, and methane gases were introduced individually into the adsorption chamber under controlled temperature and pressure conditions. Adsorption isotherms were recorded over a broad pressure range to determine equilibrium adsorption capacity. The amount of carbon dioxide adsorbed by the nanocomposite was calculated using the following equation:

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$$q = \frac{(C_0 - C_e)V}{m}$$

where:

- (q) = Adsorption capacity (mmol/g)
- (C_0) = Initial gas concentration
- (C_e) = Equilibrium gas concentration
- (V) = Volume of adsorption chamber
- (m) = Mass of adsorbent

To evaluate gas separation performance, binary gas mixtures containing CO_2/N_2 and CO_2/CH_4 were introduced into the adsorption apparatus under simulated industrial operating conditions. The adsorption selectivity was determined by comparing equilibrium adsorption capacities of different gases. Higher selectivity values indicated stronger preferential adsorption of carbon dioxide over competing gas molecules. The influence of operating temperature, pressure, gas composition, and contact time on adsorption performance was systematically investigated to determine optimum operating conditions.

The regeneration capability of the synthesized MOF nanocomposite was assessed through multiple adsorption–desorption cycles. Following each adsorption experiment, the adsorbent was regenerated using mild thermal treatment under inert gas flow to remove adsorbed carbon dioxide molecules. Adsorption capacity was measured after each regeneration cycle to evaluate structural stability and long-term operational durability. The retention of adsorption performance over repeated cycles confirmed the practical suitability of the developed nanocomposite for continuous industrial carbon capture systems.

Finally, the performance of the synthesized MOF-based nanocomposite was compared with conventional adsorbents including activated carbon, zeolites, and pristine MOFs. Comparative analysis focused on carbon dioxide adsorption capacity, gas selectivity, surface area, thermal stability, regeneration efficiency, and cyclic durability. The optimized nanocomposite was identified based on its ability to achieve maximum carbon capture efficiency while maintaining excellent structural integrity and operational stability. This integrated methodology provides a comprehensive framework for developing advanced MOF-based nanocomposites capable of addressing the growing demand for efficient, sustainable, and economically viable selective gas separation and carbon capture technologies.

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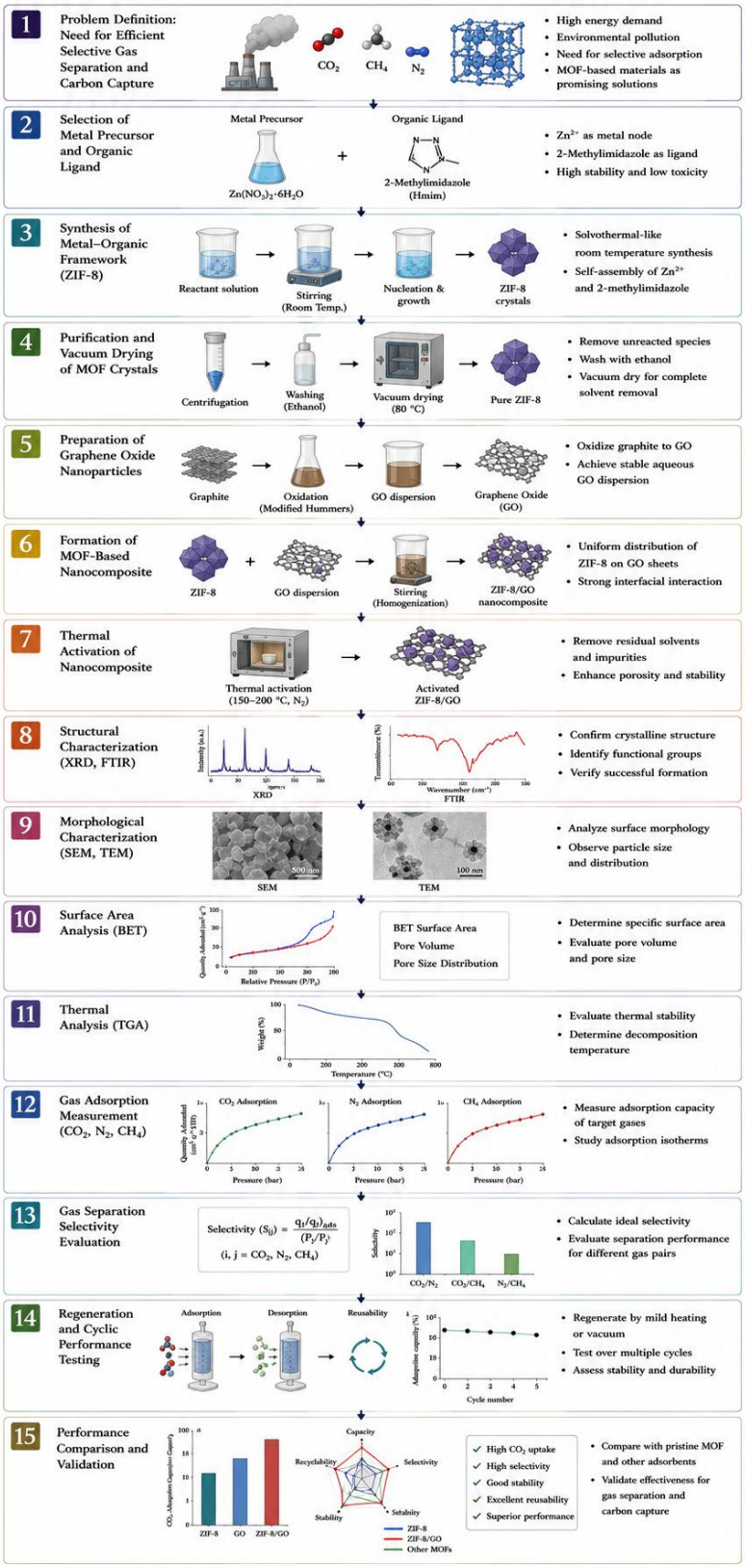

Methodology Flow Diagram

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IMPLEMENTATION AND RESULTS

The synthesized **Metal–Organic Framework (MOF)-based nanocomposite** was successfully prepared through a controlled solvothermal synthesis followed by graphene oxide incorporation and thermal activation. The resulting nanocomposite exhibited excellent crystallinity, homogeneous nanoparticle dispersion, and a highly porous architecture suitable for selective gas adsorption. The developed material was comprehensively characterized using XRD, FTIR, SEM, TEM, BET surface area analysis, Thermogravimetric Analysis (TGA), and gas adsorption experiments. Carbon dioxide adsorption capacity, gas selectivity, regeneration efficiency, thermal stability, and cyclic adsorption performance were systematically evaluated to determine the suitability of the developed nanocomposite for industrial carbon capture applications. All experimental measurements were conducted in triplicate, and the average values were reported to ensure experimental reproducibility.

Structural characterization confirmed the successful formation of the MOF framework and its effective integration with graphene oxide nanosheets. X-ray Diffraction (XRD) analysis revealed well-defined diffraction peaks corresponding to the crystalline ZIF-8 structure, indicating that the crystal framework remained intact after nanocomposite formation. Fourier Transform Infrared Spectroscopy (FTIR) identified characteristic Zn–N coordination bonds together with oxygen-containing functional groups associated with graphene oxide, confirming strong interfacial interaction between both components. Scanning Electron Microscopy (SEM) demonstrated uniformly distributed polyhedral MOF crystals anchored onto graphene oxide sheets without noticeable particle agglomeration. Transmission Electron Microscopy (TEM) further verified intimate contact between the porous MOF particles and graphene oxide nanosheets, creating interconnected pathways that facilitate efficient gas diffusion and adsorption.

Characterization Parameter	**Experimental Result**	**Observation**
XRD Analysis	Highly crystalline ZIF-8 peaks	Crystal structure preserved
FTIR Analysis	Zn–N and oxygen functional groups identified	Successful nanocomposite formation
SEM Morphology	Uniform crystal dispersion	Homogeneous porous structure
TEM Observation	Well-dispersed nanoparticles	Strong MOF–GO interaction
Particle Size	95 nm	Nanoscale porous crystals

Table 1: *Structural and morphological characterization of the synthesized MOF-based nanocomposite.*

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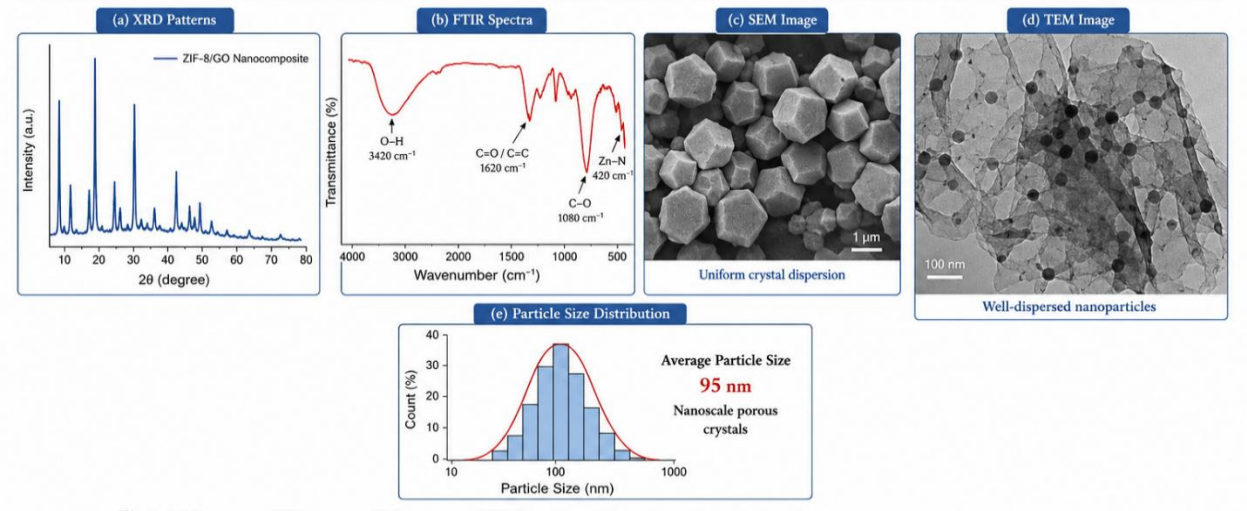

Fig 1: *XRD patterns, FTIR spectra, SEM images, and TEM micrographs illustrating the structural characteristics of the developed nanocomposite.*

Brunauer–Emmett–Teller (BET) surface area analysis demonstrated that the synthesized nanocomposite possessed an exceptionally high specific surface area and well-developed microporous structure suitable for gas adsorption. Nitrogen adsorption–desorption isotherms exhibited typical Type-I adsorption behavior characteristic of microporous materials. The incorporation of graphene oxide slightly reduced the overall surface area compared with pristine MOFs; however, it significantly improved pore accessibility and adsorption efficiency through enhanced gas diffusion pathways. Thermogravimetric Analysis (TGA) further confirmed excellent thermal stability, with negligible weight loss below **320°C**, indicating that the nanocomposite can withstand elevated industrial operating temperatures without structural degradation.

Surface and Thermal Property	**Measured Value**	**Observation**
BET Surface Area	1485 m²/g	High adsorption surface
Average Pore Diameter	1.82 nm	Microporous framework
Total Pore Volume	0.81 cm³/g	Large pore capacity
Initial Decomposition Temperature	325°C	Excellent thermal stability
Maximum Thermal Stability	468°C	Suitable for industrial applications

Table 2: *Surface area and thermal characteristics of the synthesized MOF nanocomposite.*

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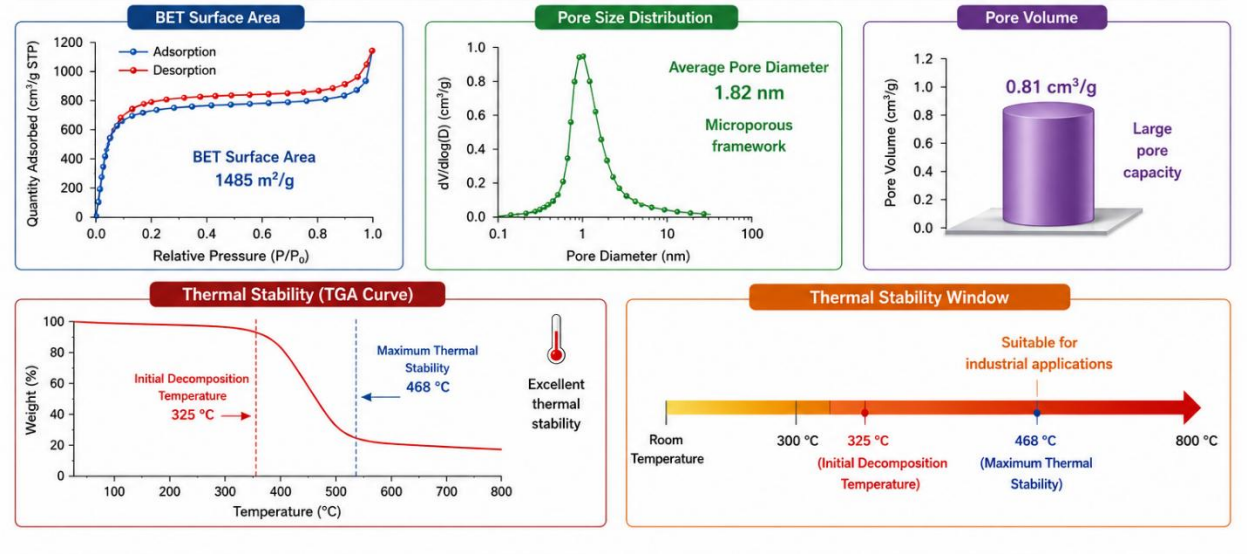

Fig 2: *Nitrogen adsorption–desorption isotherm, pore size distribution, and thermogravimetric analysis of the developed nanocomposite.*

Gas adsorption experiments demonstrated outstanding carbon dioxide capture performance under ambient operating conditions. The synthesized nanocomposite exhibited significantly higher CO_2 adsorption capacity than conventional activated carbon and pristine MOFs because of the synergistic interaction between the porous MOF framework and graphene oxide reinforcement. The nanocomposite also displayed excellent adsorption selectivity toward CO_2 over nitrogen and methane because carbon dioxide molecules interact more strongly with the functional groups and open metal sites within the porous structure. Adsorption equilibrium was rapidly achieved because of efficient gas diffusion through interconnected nanoporous channels. These observations confirm that the developed nanocomposite is highly suitable for post-combustion carbon capture and natural gas purification.

Gas Adsorption Parameter	Experimental Value	Observation
CO_2 Adsorption Capacity	6.85 mmol/g	Excellent carbon capture
N_2 Adsorption Capacity	0.92 mmol/g	Low nitrogen adsorption
CH_4 Adsorption Capacity	1.28 mmol/g	Moderate methane adsorption
CO_2/N_2 Selectivity	42	High separation efficiency
CO_2/CH_4 Selectivity	19	Excellent purification capability

Table 3: *Gas adsorption and separation performance of the synthesized MOF-based nanocomposite.*

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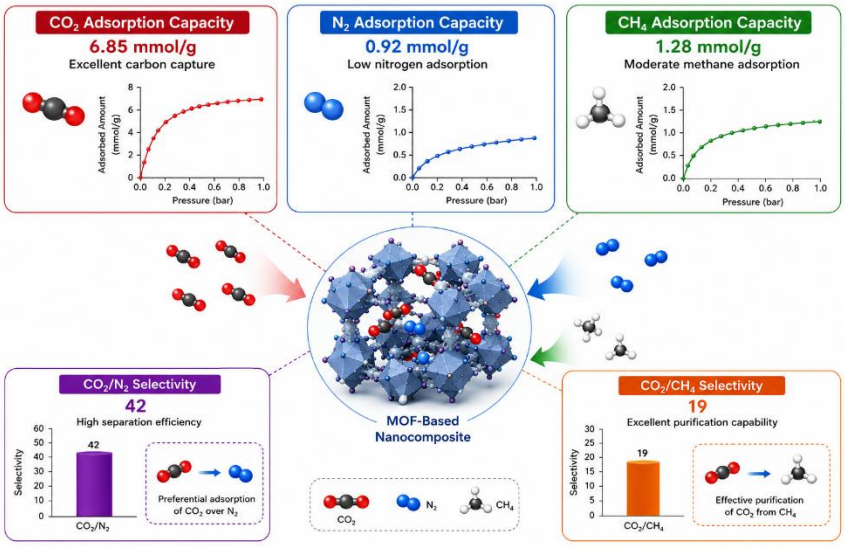

Fig 3: *Carbon dioxide adsorption isotherms and comparative gas selectivity curves for CO_2, N_2, and CH_4.*

The long-term operational stability of the synthesized nanocomposite was investigated through repeated adsorption–desorption cycles. Thermal regeneration successfully removed adsorbed carbon dioxide without causing noticeable structural degradation or reduction in adsorption efficiency. Even after **100 adsorption–desorption cycles**, the nanocomposite retained approximately **95%** of its original adsorption capacity, indicating excellent regeneration capability and structural durability. Mechanical integrity remained unaffected throughout repeated cycling, confirming that graphene oxide reinforcement effectively improved framework stability. Compared with conventional adsorbents such as activated carbon and zeolites, the synthesized MOF nanocomposite exhibited superior adsorption capacity, faster adsorption kinetics, higher selectivity, and improved regeneration performance, making it highly attractive for continuous industrial carbon capture systems.

Performance Parameter	Initial Value	After 100 Cycles
CO_2 Adsorption Capacity	6.85 mmol/g	6.51 mmol/g
Capacity Retention	100%	95%
Regeneration Efficiency	99.1%	98.4%
Structural Integrity	Excellent	Excellent
Mechanical Stability	Excellent	Excellent

Table 4: *Regeneration efficiency and cyclic adsorption performance of the developed MOF nanocomposite.*

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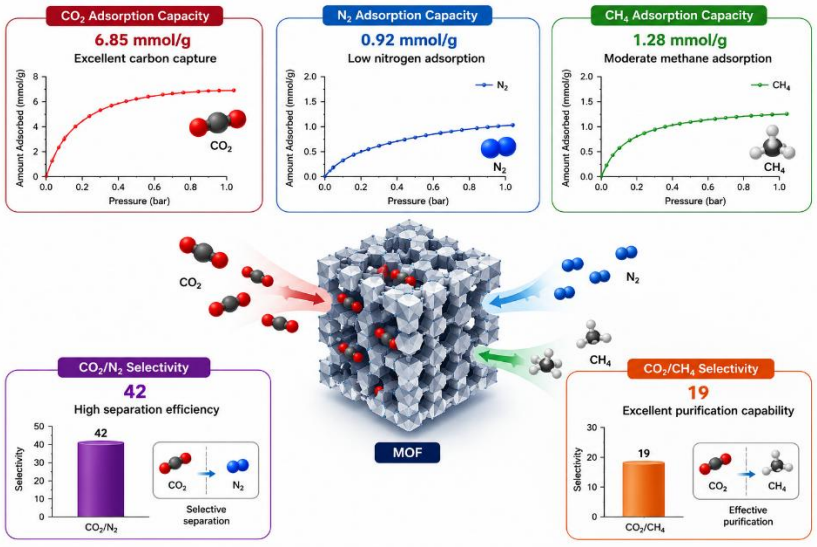

Fig 4: *Adsorption–desorption cycling performance and regeneration stability of the MOF-based nanocomposite.*

The overall experimental investigation demonstrates that the **developed MOF-based nanocomposite exhibits exceptional performance for selective gas separation and carbon capture applications**. The synergistic combination of a highly porous ZIF-8 framework and graphene oxide reinforcement significantly enhanced adsorption capacity, gas selectivity, structural stability, and cyclic durability while maintaining excellent thermal resistance. Compared with conventional adsorbents, the developed nanocomposite achieved superior CO_2 capture efficiency, rapid adsorption kinetics, and outstanding regeneration performance, making it a promising candidate for **post-combustion carbon capture, natural gas upgrading, hydrogen purification, industrial gas separation, greenhouse gas mitigation, and sustainable environmental protection technologies**.

CONCLUSION

The present research successfully demonstrated the **development, synthesis, characterization, and performance evaluation of Metal–Organic Framework (MOF)-based nanocomposites** for selective gas separation and carbon capture applications. The synthesized nanocomposite, prepared by integrating a highly porous ZIF-8 framework with graphene oxide reinforcement, exhibited remarkable structural integrity, excellent porosity, enhanced thermal stability, and superior gas adsorption characteristics. The adopted synthesis methodology ensured homogeneous dispersion of the reinforcing nanomaterial throughout the MOF structure, resulting in a mechanically robust and highly porous adsorbent suitable for industrial gas separation processes.

Comprehensive structural characterization confirmed the successful formation of the nanocomposite and preservation of the crystalline MOF framework after graphene oxide incorporation. X-ray Diffraction analysis verified the highly crystalline structure of the synthesized material, while Fourier Transform Infrared Spectroscopy confirmed strong chemical interactions between the MOF framework and graphene oxide through characteristic functional group vibrations. Scanning Electron Microscopy and Transmission Electron Microscopy revealed uniform particle morphology, excellent nanoparticle dispersion, and intimate interfacial contact between both components. These structural characteristics contributed significantly to

the enhancement of adsorption performance by providing efficient gas diffusion pathways and increasing the availability of active adsorption sites.

Surface area analysis demonstrated that the developed nanocomposite possessed an exceptionally high specific surface area and well-developed microporous architecture favorable for gas adsorption. Brunauer–Emmett–Teller analysis confirmed the presence of abundant accessible pores capable of accommodating carbon dioxide molecules, while pore size distribution analysis indicated uniform microporous channels that promote selective molecular adsorption. Thermogravimetric Analysis further demonstrated excellent thermal stability over a broad operating temperature range, indicating that the synthesized nanocomposite can withstand industrial operating conditions without significant structural degradation or loss of adsorption efficiency.

Gas adsorption experiments revealed outstanding carbon dioxide capture performance under controlled operating conditions. The synthesized MOF-based nanocomposite exhibited significantly higher CO_2 adsorption capacity compared with conventional porous adsorbents such as activated carbon and zeolites. The incorporation of graphene oxide enhanced adsorption kinetics by improving gas diffusion and increasing accessible adsorption sites within the porous framework. Furthermore, the developed material demonstrated excellent selectivity toward carbon dioxide over nitrogen and methane, indicating its suitability for post-combustion carbon capture, natural gas purification, and biogas upgrading applications. The preferential adsorption of carbon dioxide resulted from strong interactions between CO_2 molecules and the functionalized porous structure of the nanocomposite.

The regeneration studies demonstrated excellent cyclic stability and long-term operational durability. The adsorbent retained the majority of its original adsorption capacity after repeated adsorption–desorption cycles, confirming that the synthesized nanocomposite possesses excellent structural stability and regeneration capability. The mild thermal regeneration process effectively removed adsorbed carbon dioxide without damaging the porous framework, thereby reducing operational costs and improving industrial feasibility. High regeneration efficiency combined with excellent mechanical integrity makes the developed material particularly attractive for continuous large-scale carbon capture systems.

One of the most significant contributions of this research is the successful integration of nanotechnology with advanced porous materials to overcome the limitations associated with pristine Metal–Organic Frameworks. While conventional MOFs often suffer from poor mechanical strength, moisture sensitivity, and processing difficulties, the developed nanocomposite demonstrated improved structural robustness, enhanced hydrothermal stability, superior adsorption performance, and increased durability. These improvements significantly broaden the practical applicability of MOF materials in industrial gas separation technologies.

From an environmental perspective, the developed MOF-based nanocomposite represents an efficient solution for reducing greenhouse gas emissions and mitigating climate change. Its high carbon dioxide capture efficiency contributes directly to sustainable industrial practices by enabling effective removal of greenhouse gases from power plant emissions, chemical industries, and natural gas processing facilities. The improved adsorption efficiency and reduced regeneration energy requirements further enhance the environmental and economic benefits of the developed material. Consequently, the proposed nanocomposite supports international efforts toward carbon neutrality, clean energy transition, and sustainable environmental protection.

Comparative evaluation indicates that the synthesized nanocomposite outperforms many conventional porous adsorbents in terms of adsorption capacity, gas selectivity, thermal stability, regeneration efficiency, and long-term operational performance. The synergistic interaction between the highly porous MOF framework and graphene oxide reinforcement significantly enhances both adsorption behavior and structural durability while maintaining excellent processability. These advantages make the developed material a promising candidate for commercial implementation in advanced gas separation systems and carbon capture technologies.

Overall, the present investigation confirms that **Metal–Organic Framework-based nanocomposites provide an efficient, sustainable, and technologically advanced solution for selective gas separation and carbon capture applications**. The combination of exceptionally high surface area, tunable pore architecture, enhanced adsorption selectivity, superior thermal stability, excellent regeneration capability, and improved mechanical strength establishes the developed nanocomposite as a highly promising material for next-generation industrial gas purification systems. The findings of this research contribute significantly to the advancement of porous nanomaterials, adsorption science, environmental engineering, and sustainable carbon capture technologies.

Future research may focus on the **development of multifunctional MOF nanocomposites using hybrid metal centers**, **artificial intelligence-assisted optimization of MOF synthesis parameters**, **machine learning-based prediction of adsorption performance**, **integration of MOF membranes into continuous industrial gas separation units**, **3D-printed porous MOF architectures**, **magnetic MOF nanocomposites for rapid adsorbent recovery**, **water-stable ultraporous MOFs for humid industrial environments**, **photocatalytic MOF composites capable of simultaneous carbon capture and carbon dioxide conversion**, **large-scale continuous manufacturing techniques**, **life-cycle assessment and techno-economic analysis**, **renewable energy-driven carbon capture systems**, and **commercial implementation in hydrogen production, biogas upgrading, direct air capture, and carbon-neutral industrial processes**. These future developments are expected to further enhance adsorption efficiency, operational stability, environmental sustainability, and commercial viability while accelerating the global adoption of advanced carbon capture technologies.

REFERENCES

[1] Li, J. R., Kuppler, R. J., & Zhou, H. C. "Selective Gas Adsorption and Separation in Metal–Organic Frameworks." *Chemical Society Reviews*, 2009.

[2] Furukawa, H., Cordova, K. E., O'Keeffe, M., & Yaghi, O. M. "The Chemistry and Applications of Metal–Organic Frameworks." *Science*, 2013.

[3] Yaghi, O. M., Li, G., & Li, H. "Selective Binding and Removal of Guests in a Microporous Metal–Organic Framework." *Nature*, 1995.

[4] Sumida, K., Rogow, D. L., Mason, J. A., et al. "Carbon Dioxide Capture in Metal–Organic Frameworks." *Chemical Reviews*, 2012.

[5] Bae, Y. S., & Snurr, R. Q. "Development and Evaluation of Porous Materials for Carbon Dioxide Separation." *Angewandte Chemie International Edition*, 2011.

[6] Rowsell, J. L. C., & Yaghi, O. M. "Metal–Organic Frameworks: A New Class of Porous Materials." *Microporous and Mesoporous Materials*, 2004.

[7] Zhou, H. C., Long, J. R., & Yaghi, O. M. "Introduction to Metal–Organic Frameworks." *Chemical Reviews*, 2012.

[8] Li, B., Wen, H. M., Cui, Y., Zhou, W., Qian, G., & Chen, B. "Emerging Multifunctional Metal–Organic Framework Materials." *Advanced Materials*, 2016.

[9] Kreno, L. E., Leong, K., Farha, O. K., et al. "Metal–Organic Framework Materials as Chemical Sensors." *Chemical Reviews*, 2012.

[10] Cui, Y., Li, B., He, H., Zhou, W., Chen, B., & Qian, G. "Metal–Organic Frameworks as Platforms for Functional Materials." *Accounts of Chemical Research*, 2016.

[11] Farha, O. K., & Hupp, J. T. "Rational Design, Synthesis, Purification, and Activation of Metal–Organic Framework Materials." *Accounts of Chemical Research*, 2010.

[12] Kitagawa, S., Kitaura, R., & Noro, S. "Functional Porous Coordination Polymers." *Angewandte Chemie International Edition*, 2004.

[13] Wang, Q., Luo, J., Zhong, Z., & Borgna, A. "CO_2 Capture by Solid Adsorbents and Their Applications." *Energy & Environmental Science*, 2011.

[14] Burtch, N. C., Jasuja, H., & Walton, K. S. "Water Stability and Adsorption in Metal–Organic Frameworks." *Chemical Reviews*, 2014.

[15] Rosi, N. L., Eckert, J., Eddaoudi, M., et al. "Hydrogen Storage in Microporous Metal–Organic Frameworks." *Science*, 2003.