Available online at www.jourcc.com

Journal homepage: www.JOURCC.com

Journal of Composites and Compounds

A critical review about metal organic framework-based composites: Potential applications and future perspective

Hicham Meskher [a]*

[a] *Division of Process Engineering, College of Applied Science, Kasdi-Merbah University, Ouargla, 30000, Algeria*

ABSTRACT

The properties of metal-organic frameworks (MOFs), a potential class of porous crystalline materials with a wide range of uses, depend on their structural details, including compositions and architectural designs. Through functionalization and their interaction with other nanomaterials, MOFs' structure and design have undergone changes as a result of their extensive research. Numerous outstanding evaluations on single MOFs, MOF-based composites created through conjugation with non-MOF materials, and their derivatives have summarized the developments in the field of MOFs. A thorough examination of MOFs and their combination is, however, lacking. In this perspective, we present a current and thorough description of the accomplishments of MOF-based hybrids below. First, a description of the synthetic strategy/formation process is provided to illustrate how host and visitor MOFs interact. The structural diversity in MOF-based systems is then thoroughly examined to show how MOF systems enable advancements in abased composites for a variety of applications, particularly in the medical and environmental fields. Finally, we present our personal opinions on the difficulties and potential paths for the development of MOFs materials.

ARTICLE INFORMATION

Article history:
Received 17 December 2023
Received in revised form 26 January 2023
Accepted 11 March 2023

Keywords:
Metal organic framework
Synthetic strategy
Application
Nanohybrids
Metal nanoparticles

Table of contents

1. Introduction

Bivalent or trivalent aromatic carboxylic acids or N-containing aromatics are frequently utilized to build frameworks with gold, zinc, copper, chromium, aluminum, zirconium, and other elements in metal organic frameworks (MOFs), a family of crystalline organic-inorganic hybrid compounds [1-4]. The structure of the framework, inorganic metal centers, and organic ligands are the three primary components of MOF. If MOFs were created by expanding zeolite topology, their inorganic and organic structures would have larger pores and higher porosity than zeolites. The enlarged size of inorganic SBUs and the network's

---

* *Corresponding author: Hicham Meskher; E-mail:* hicham.meskher@g.enp.edu.dz

https://doi.org/10.61186/jcc.5.1.5.

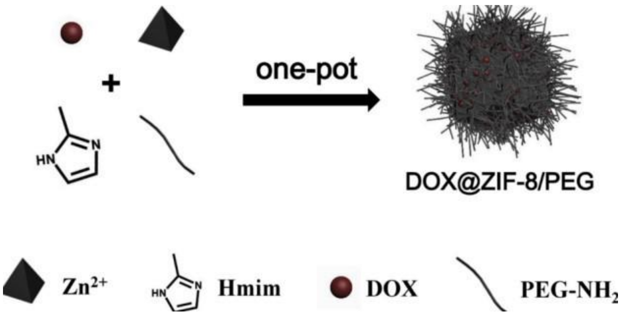

Fig. 1. One-pot synthesis of poly(ethylene glycol) modified zeolitic imidazolateframework-8 nanoparticles: Size control, surface modification and drug encapsulation. Reproduced from Elsevier [35].

dimensions caused by big metal clusters are the causes of the huge pore size. Additionally, a combination of high porosity and longer organic ligands that benefit big pore width account for the length of the link between inorganic SBU. When various metal centers and ligands are used to create MOFs as molecular building blocks, the resulting flexibility allows for the modification of both physical and chemical properties [5]. MOFs are synthesized through various procedures such as surface modified encapsulation, in situ generation in MOF's cavities, self-sacrificed template method, microwave assisted methods, room temperature based procedures, step-by-step construction of the sandwich-like heterostructure, and one pot synthetic method [2,3,6,7]. Due to MOFs' exceptional qualities, these materials are now widely used in a variety of fields, including medication delivery, sensing, and gas storage [8,9]. The syntheses of MOF-based composites or their use in the catalysis or sensing domains were the focus of many outstanding publications that discussed the synergistic effect between MOFs. In contrast, it is currently unclear how the functions of MOF component parts relate to their actual applications. In fact, according to some studies, MOFs' distinct internal structures and properties—rather than those of other integrated functional materials—are the primary cause of the improved performances and expansion of MOF-based composite functionalities. Therefore, it is crucial to clarify the function of MOFs in composites in order to comprehend how the structure and functionality of materials based on MOFs relate to one another.

This paper summarizes current developments in MOF-based composites in an effort to better understand the structure-performance relationship of MOF-based composites, with a focus on the practical uses of MOF components. First, common techniques for producing MOF-based composites are discussed, along with benefits and drawbacks. Next, according to the functions of MOF components in MOF-based composite applications, the impact of internal composition, structures, and properties of MOFs as well as external encapsulation status characteristics on the performance of composites is discussed, with a focus on their use in the medical field and environmental remediation. Then, contemporary problems with these composites are given and discussed. To further pique the curiosity of chemical aficionados, we think that the review will give readers a better grasp of MOF-based composites for more carefully managed manufacturing and application.

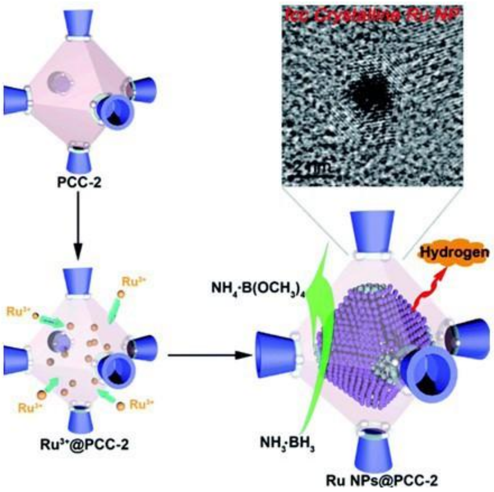

Fig. 2. Scheme representing the synthesis of fcc Ru NPs via PCC-2 as the template. Reproduced with permission from Elsevier [37].

2. MOF-based composites

The crystalline porous materials known as Metal-Organic Frameworks (MOFs) are created when core metal ions or clusters self-assemble with bidentate or multidentate organic ligands using coordination bonds [1,10]. Since their discovery in the early 1990s, MOFs have been the subject of intense research because of their highly organized porosity, extraordinarily high internal surface areas, and adaptable architectures. As a result, MOFs swiftly gained popularity as materials for almost two decades [11]. Up to this point, significant efforts have been made to create MOFs with novel structures and properties and to explore their potential uses in a variety of industries, including gas adsorption/separation, catalysis, sensors, drug delivery, magnetic materials, and optical devices [12-14].Unfortunately, there are several instances where the performance of MOF materials is less than ideal, and there is still much work to be done to increase their applicability [15].

MOFs have advantages over conventional porous materials in terms of shape and characteristics, allowing open channels to be constructed and carefully tuned utilizing various metal nodes and organic ligands in accordance with intended uses [16]. MOFs are excellent host platforms for the immobilization or encapsulation of various functional materials, such as nanoparticles (NPs), quantum dots, polyoxometalates, enzymes, and polymers, because of their structural diversity and adaptability [17-19]. As a result of the materials' synergy, MOF composites always display significantly improved or even unique features when compared to single-component materials [20].

Technically, the constrained environment produced by the MOF cavities might significantly increase the catalytic activity of embedded NP catalysts [21]. MOF composites may be used to create sensors that can identify the size of molecules by utilizing the barrier effect in MOF channels on the flow of foreign molecules [22]. Additionally, it was discovered that after being enclosed in MOFs, fragile enzymes may display great tolerance under challenging circumstances while maintaining high activity [6,15,23]. In order to further improve their performances and broaden their applications, MOF-based composites have drawn growing research attention. As a result, significant effort has gone into designing and building different MOF-based composites. However, despite the great progress, achieving functionality between the MOF host and guest species is still challenging for specific applications of MOF-based composites. Hence, it is vital to identify the structural–functional relationship in MOF composites to efficiently and directionally synthesize specific MOF composites for particular applications.

The synergistic relationship between MOFs and other functional materials has already been covered in a number of outstanding reviews [26,27]. The majority of them concentrated on the creation of MOF-based composites or on using them in catalysis or sensing sectors [28] . In contrast, it is currently unclear how the functions of MOF component

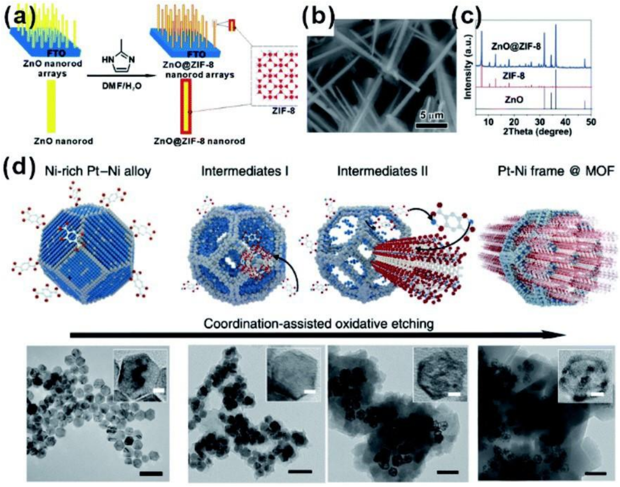

Fig. 3. Schematic of ZnO@ZIF-8 nanorods made using the self-template method is shown in Fig. 3(a). (b) A SEM image of ZnO@ZIF-8 nanorods, and (c) an XRD pattern. Reproduced with permission from ACS [39].

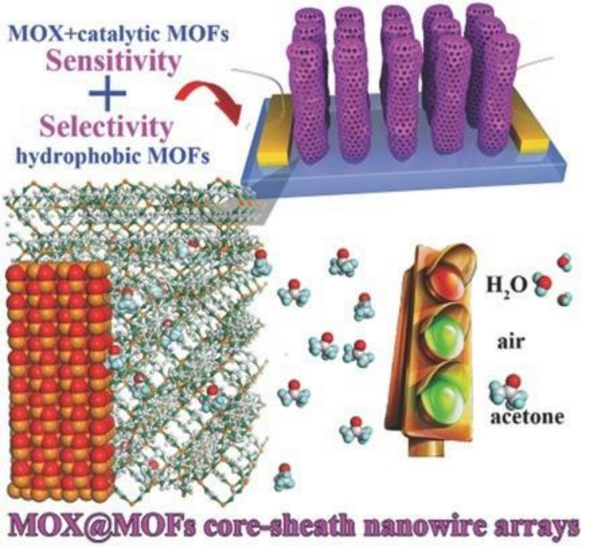

Fig. 4. For the first time, a method for creating novel materials for sensing volatile organic molecules is proposed, combining metal oxides and metal-organic frameworks.

parts relate to their actual applications. In fact, some research revealed that instead of the properties of other integrated functional materials, the better performances and expansion of MOF-based composite functions mostly originate from the unique internal structures and properties of MOFs [29]. In order to better comprehend the relationship between the structure and function of MOF-based materials, it is crucial to clarify the role of MOFs in composites.

Many different combinations of nanomaterials and MOFs can be used to create MOFs-based composites, which enable the achievement of a wide range of functions and characteristics. Composites made from MOFs are appealing for a variety of applications due to their many benefits. Several of these benefits include:

High surface area: Composites based on MOFs have high surface areas, making them suitable for catalytic and adsorption processes.

Porosity: Composites based on MOFs are porous, which makes them good for storing and separating gases.

Tunable characteristics: A wide range of functionalities and properties can be attained by synthesizing MOFs-based composites from a variety of metal ions and organic ligands.

Chemical stability: Composites based on MOFs may exhibit strong chemical stability, making them appropriate for usage in challenging conditions.

Synthesis simplicity:Scalable production is made possible by the simple and moderate synthetic conditions that may be used to easily produce MOFs-based composites.

Crystalline structure: MOFs-based composites may be characterized by X-ray diffraction and designed with the aid of computational models thanks to their clearly defined crystalline structure.

3. Synthesis

The properties and the performances of MOF-based composites are directly related to the MOFs structure, design and structure. For the synthesis of MOF-based composites, there five roots could be used; (i) surface modified encapsulation, (ii) in situ generation in MOF's cavities, (iii) self-sacrificed template method, (iv) step-by-step construction of the sandwich-like heterostructure, and (v) one pot synthetic method.

3.1. Surface modified encapsulation

This technique also called "build-bottle-aroundship" and it is based on two major steps: (i) preparation of well performed NPs with unique and uniform size, design, structure and morphology and then (ii) the MOF will be grown on the surface of the prepared NPs creating great lattice structure barriers between MOFs and encapsulated materials, leading to self-nucleation of MOFs instead of forming the encapsulation structure. To overcome such barriers, structure-flexible materials have been used bridges to connect MOFs with encapsulated materials.

For instance, to correct the lattice mismatch at NP@MOF surfaces, several authors treated NPs with surfactants PVP and CTAB afterwards [30]. In addition to surfactants, metal oxides or hydroxides may be used to alter NPs and build MOFs [31,32]. NPs of different shapes and sizes can be enclosed inside MOF shells using encapsulation. Other materials, including carbon-based compounds, polymers, and even enzymes, might be employed in place of these nanoparticles to modify the MOFs surfaces using this technique [33,34].

Unfortunately, this technique could be time-consuming which require more effort to find new rots and alternative to improve this technique. In this context, a study reported a simple and rapid synthetic method that combines the size control of ZIF-8 NPs and their surface modification of PEG at the same time. Monovalent amino PEG (PEG-NH_2) was used as capping agent to control the size of ZIF-8 and simultaneously realize surface modification through coordination interaction. The size of ZIF-8 was tuned in a board range. The coated NPs showed intact crystalline structure with improved colloidal stability. By further adding the anticancer drug doxorubincin (DOX) into the reaction mixture, ZIF-8 NPs with encapsulated DOX and PEG surface modification (DOX@ZIF-8/PEG) can be synthesized in one-pot (figure 1) [35].

3.2. In situ generation in MOF cavities

This method involves first diffusing precursors of the embedded material into the MOF cavities, then in situ transforming the target materials there. Here, the difficult issue is the production of the materials utilized for modifications in the cavities of the MOFs rather than on their surfaces, which may restrict the applications of this technology and also restrict the performance of the created MOF-based composites [36].

Nevertheless, there are still some issues with in situ generation. First off, the interior structures of MOF templates may be somewhat damaged during the process of forming embedded materials. Additionally, it is difficult to comprehend the structure-performance relationship of MOF-based composites since it is difficult to manage the morphology, surface structure, and density of embedded elements.

The in situ generation method has produced NPs with pristine surface topographies without modification with organic surfactants like CTAB and PVP. Additionally, NPs constrained by MOF cavities seemed

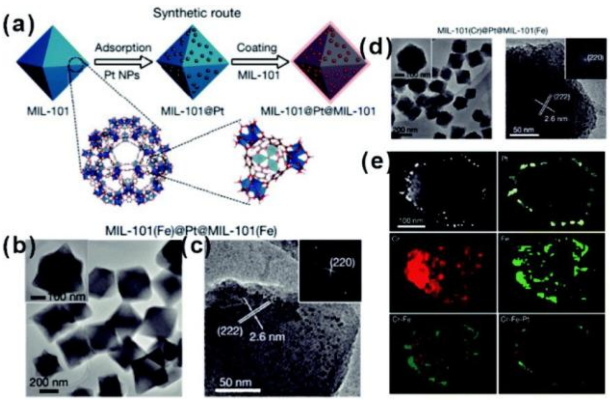

Fig. 5. Synthetic process of sandwiched MIL-101@Pt@MIL-101 composites is shown in Fig. 5(a). (b and c) TEM pictures of the MIL-101(Fe)@Pt@MIL-101 in their prepared state (Fe). (d) TEM images of the MIL-101(Cr)@Pt@MIL-101(Fe) as prepared; (e) associated HAADF-STEM image; and (f) elemental mapping images. Reproduced with permission from nature [48].

relatively tiny and consistent in size, advantageous for real-world uses. Surprisingly, under benign conditions, an in situ reaction in MOF cavities serving as nanoreactors can easily produce NPs with certain unique shapes and compositions. For instance, using a truncated octahedral inner cavity (diameter 2.5 nm) of a porous coordination cage (PCC-2) as the nanoreactor, Zhou et al. created uniform truncated octahedral face-centered-cubic (fcc) ruthenium (Ru) NPs with exposed 111 and 100 planes, which is frequently challenging [37].

3.3. Self-sacrificed template method

Controlling the encapsulation status of embedded elements within the MOF matrix alone is crucial for MOF-based composites since it has a substantial impact on the practical performances, particularly in catalysis and sensing. Although many different approaches to building well-defined NP@MOF composites have been tried, it can be difficult to identify generalized paths. The self-sacrificed template technique works well for creating hollow or core-shell nanostructures because of the characteristics of solid reaction and relatively slow kinetics [7,38].

(d) A diagram of the coordination-assisted oxidative etching procedure and the related TEM images (scale bars represent 50 nm). Magnified TEM pictures are insets (scale bars represent 5 nm). Reproduction permitted. Nature Publishing Group [40].

Finding the right template materials and reaction conditions is essential for the successful fabrication of NPs@MOF composites using a self-sacrificed template. The release rate of metal ions from the template must match the coordination rate with organic linkers in order to ensure the formation of the MOF shell on the self-sacrificed template surface rather than in solution. Our team was the first to create metal oxide semiconductor@MOF composites using the self-sacrificed template method; ZnO nanorods served as both a template and a source of Zn for the creation of ZIF shells [39]. Both metal oxides and alloys containing transition metals can be used as template materials in the self-sacrificed template approach, which is straightforward and applicable to all materials [39,41].For instance, Wu and Li et al. effectively created PtNi@MOF-74 composites using a coordination-assisted oxidative etching technique by using PtNi alloy NPs as a template [40].

The self-sacrificed template route has some limitations when it comes to template selection when compared to other approaches, but it provides a possible route to finely control the structure, thickness, and morphology of MOF shells. For example, the research team successfully controlled the thickness of the MOF shell in the nanoflower-like RhNi@MOF-74(Ni) synthesis by tuning the Ni content in the self-sacrificed RhNi alloy template [41]. Additionally, we employed 2,5-dihydroxyterephthalic acid or 2-methylimidazole as etching agents to selectively dissolve Ni or Co components of RhCoNi ternary alloy NCs to create MOF-74(Ni) and ZIF-67(Co) shells, respectively, on the alloy surface [42]. The as-prepared composites appeared promise as adaptable platforms to comprehensively explore the relationship between performance of composites and structure of MOF shells due to the significant disparities between the two obtained MOF shells in terms of aperture/cavity size. Another metal source can be added while MOFs are still being formed to create multicomponent MOF shells [43].

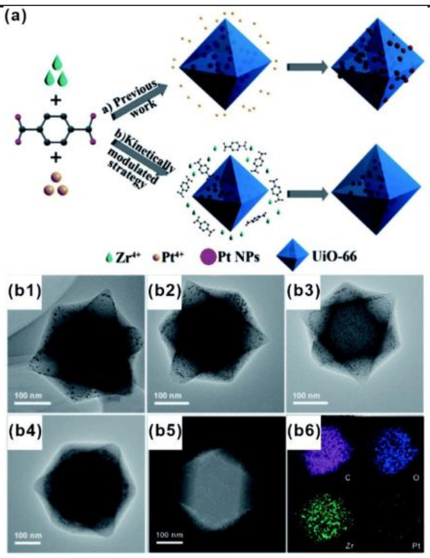

Fig. 6. MOF properties and their applications in gas storage and separation. Reproduced with permission from Elservier [61].

The self-sacrificed template method was used to create several MOF-based devices in sensor and catalysis applications in addition to creating MOF-based composite nanoparticles [44]. By depositing a layer of ZIF-CoZn thin film on a ZnOnanowire array using a self-sacrificed template approach, for instance, the ZnO@ZIF-CoZn gas sensor was created. Foreign Co2+ was also engaged in the synthesis of ZnO@ZIF-CoZn, in addition to the dissolved Zn2+ from the ZnO nanorod, which resulted in the development of the dual metal MOF thin film on the ZnO nanowire array [45].

The constructed ZnO@ZIF-CoZn core-sheath nanowire arrays exhibit significantly improved performance in terms of selectivity, responsiveness, recovery behavior, and working temperature.Reproduced with permission from wiley [45].

As a result, the self-sacrificed template method's outstanding controllability gives more room to construct various structured MOFs on the NP catalyst surface, permitting detailed investigation of the structural-functional relationship in MOF-based composites.

3.4. Step-by-step construction of the sandwich-like heterostructure

As was already indicated, it can be difficult to limit the creation of functional materials inside or outside MOF matrices. Not only does the random distribution of functional NPs in the MOF matrix result in poor practical repeatability of MOF-based composites, but it also has a significant impact on the investigation of the true structure-function connection. Tang et al. created sandwich-like MOF-supported metal catalysts to address this issue by growing additional MOF layers on top of the catalysts [46,47].

They first created MIL-101 that was loaded with Pt NPs, and then, around the already-made Pt@MIL-101 particles, they epitaxially developed a new MIL-101 shell with a variable thickness [48]. Due to the fact that all Pt NPs were encapsulated in the incredibly thin MIL-101

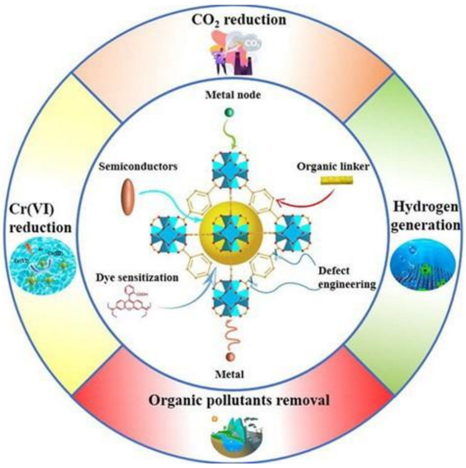

Fig. 7. Modified UiO-66 as photocatalysts for boosting the carbon-neutral energy cycle and solving environmental remediation issues. Reproduced with permission from Science direct [100].

layer, substance diffusion was unaffected (Fig. 6). When hydrogenating the C-O functional groups of a,b-unsaturated aldehydes, the resultant MIL-101@Pt@MIL-101 sandwich-like catalysts displayed remarkable selectivity. Be aware that the total catalytic efficiency of sandwich-like heterostructures depends critically on the thickness of the outer MOF shell. Thick shells will impede reactant and product diffusions, significantly lowering the reaction conversion even though selectivity should be increased to the same degree [47].

3.5. One-pot synthetic method

Each of the strategies discussed above requires a number of steps. In fact, a few instances showed how MOF-based composites might be made in a single step. For instance, Liu, Tang, and colleagues directly combined MOF-5 and Au precursors to create Au@MOF-5 [49]. The core-shell structures were produced by one-pot synthesis, where the Au precursor was first converted to Au NPs by dimethyl formamide (DMF), and then MOF-5 spontaneously developed newly generated Au NP surfaces. One-pot synthesis depends on controlling the development rate of MOFs and/or the rate at which metal ions reduce. As a result, Luque and Li et al. were successful in controlling the encapsulation of “clean” Pt clusters within UIO-66 by using a unique, kinetically controlled, one-step technique [50,51]. The use of a DMF solvent was crucial to the method’s success. In order to create Pt/UiO-66 composites, DMF and its minor byproduct of oxidation (Me2NCOOH) would serve as a “bridge” to join MOF precursors to as-reduced Pt clusters, causing MOFs to develop anisotropically around the Pt surface. Although relatively straightforward and effective, one-pot synthesis is sadly not a widely used tactic. A group of substances known as metal-organic frameworks (MOFs) are composed of metal ions or clusters joined by organic ligands. They are highly porous materials with tunable properties that are appealing for a variety of applications, including gas storage, separation, and catalysis. Figure 6. Pt NPs are incorporated into MOFs using an in situ one-step technique and an in situ one-step strategy with kinetic modulation (Fig. 7(a)). (b1-b4) TEM pictures of Pt@UiO-66 nanocomposites made using various H_2/air volume ratios. A (b5 and b6) HAADF-STEM picture of Pt@UiO-66 with the associated elemental mapping. Reproduced with permission from Wiley [51].

4. Applications

Metal-organic frameworks (MOFs) are a relatively new class of materials with a wide range of possible uses. As a result, research on them is now being conducted in both academic and professional settings. These possible uses comprise:

4.1. Gas storage and separation

Gas separation and storage are strongly tied to many facets of human life, including energy use, industrial output, and environmental protection. In particular, the separation of carbon dioxide is essential for reducing the greenhouse effect, the storage of hydrogen and methane is necessary for the widespread use of clean energy, and the separation and storage of toxic gases like carbon monoxide and ammonia are crucial for pollution control and the synthesis of industrial chemicals. An emerging family of crystalline porous materials called metal-organic frameworks (MOFs) are made of inorganic metal nodes and organic linkers, and recently they have received a plenty of applications in this field [52,53]. The distinctive structural qualities of MOFs, such as high porosity, large surface area, tunable structure, and modifiable functionality, make them particularly promising to be employed in gas storage and separation when compared to other porous materials [54,55].

In this context, researchers should concentrate more on highlighting the desired chemical properties of MOFs for required performance for precise and effective seperation of the aforementioned energy-related gases, including CO_2, H_2, and CH_4, and any additional harmful gases, such as CO and NH3. Through careful regulation of pore size, great progress has been made in the hydrocarbon separation of acetylene/ethylene and propylene/propane [56,57].

Additionally, using logically constructed MOFs, effective acetylene storage at ambient conditions was also accomplished [58]. MOFs outperform the majority of commonly used porous materials like zeolite and carbons in terms of specific surface area, which ranges from 1000 to 10,000 m^2/g. MOFs, which have such a vast surface area, are thought to have tremendous potential for storing gases like H_2 and CH_4. The key benefits of employing MOFs over conventional porous materials are their consistent pore size and controllability of the entire structure. By fine-tuning the size of the ligand, changing the functional groups on the ligand or metal sites, exchanging metal ions, or employing the cooperative regulation of ligands and metal sites, isoreticular chemistry within MOFs makes it simple to obtain high H_2, CO_2, CH_4, and C_2H_2 storage [59,60]. Recently, a number of start-up companies that make MOFs have flourished, advancing the field of employing MOFs for adsorption to a new level. In light of this, this review article tries to summarize current advances in the use of MOFs for adsorption, both in the gaseous and liquid phases, while also incorporating the foundational knowledge needed to comprehend the adsorptive capabilities of MOFs. Adsorption applications with a list of the most promising structures and adsorption mechanisms are given priority. At the conclusion of the article, a personal perspective on the field’s future developments is offered. Although by no means comprehensive, this review tries to give readers a quick overview of the most recent developments in this field of study.

4.2. Catalysis

In recent years, there has been a noticeable increase in interest in catalytic chemistry [62]. Metal organic frameworks (MOFs), a family of porous materials, have generated a lot of interest recently due to their potential for use in catalysis [63-65].

It is well recognized that the cyclization of propargylic alcohols with CO_2 is a significant industrial reaction, and noble-metal catalysts are frequently used to achieve high product yields while maintaining environmental sustainability. For this reaction, a porous, noble-metal-free framework 1 with sizable, 1.66 nm-diameter 1D channels was created. Compound 1 has high acid/base stability and can even last one month in corrosive triethylamine. Furthermore, the biological macromolecule ethisterone was an uncommon substrate for this MOF catalyst to exhibit catalytic activity [66].

In a separate study, compounds derived from manganese sulfide (MnS) were synthesized and used for the first time to activate PMS to break down the antibiotic levofloxacin (LVF) in water. In line with expectations, MnS significantly outperformed Mn_2O_3 in terms of LVF degradation efficiency via PMS activation. The findings of quenching studies, electro spin resonance identification, and electrochemical testing showed that the primary mechanism in the -MnS/PMS system was electron transfer progress. Additionally, it was determined how different environmental factors affected LVF removal and the capacity of -MnS to be reused, demonstrating the high application potential of the -MnS/PMS system. This study advances the fundamental understanding of -MnS-mediated PMS activation and offers helpful details for the actual use of manganese sulfide in water treatment [67].

Similar to this, another study revealed that copper- and calcium-based metal organic frameworks (MOFs) were successfully prepared and used as catalysts in the esterification and transesterification reactions for the manufacture of biodiesel from used cooking oil (WCO). The cubical structure of MOFs with a crystallite size of 50 nm and thermal stability below 600 °C is indicated by catalyst characterization. The catalyst has undergone testing for conversion of WCO to biodiesel, and the biodiesel samples meet ASTM requirements. The catalyst loading (X1), reaction temperature (X2), and alcohol-oil ratio (X3) are further process parameters that are improved using response surface methodology (RSM) via central composite design (CCD). To examine the dynamic interaction between process factors and biodiesel yield (YBD%), the second-order regression model is used. With the catalyst loading set at 1.0 g/100 mL, the reaction temperature at 60 °C, the alcohol-to-oil ratio at 20, and the biodiesel production at 84.5 (vol%), the ideal process parameters have been identified. The proportion of difference between experimental and projected outcomes is less than 5%, indicating good agreement. For three cycles, the regenerated catalyst significantly reduces the biodiesel production by up to 7% [68].

By adding sulfamic acid to the zeolitic imidazolate framework (ZIF-90), an effective bifunctional catalyst with synergetic Lewis and Brnsted acid sites was created in order to increase the acidic sites in catalysts to increase the conversion efficiency of microalgal lipids into biodiesel (SA). It increased the amount of Brnsted and Lewis acid sites when the sulfamic acid that joined with ZIF-90 through the imine bond (C N) delivered protons and disrupted coordinated Zn-N bonds in ZIF-90. The ratio of Brnsted acid to Lewis acid increased from 0.32 to 0.49, while the overall acidity of the ideal catalyst increased from 0.478 to 0.848 mmol/g. While Brnsted acid sites in bifunctional catalysts were more active in esterification reactions of free fatty acids, Lewis acid sites were more active in transesterification reactions of triglycerides in microalgal lipids. The result was that the best catalyst increased the conversion efficiency of microalgal lipids into biodiesel from 80.6% to 98.3% at 200 °C, while conversion efficiency remained 91.7% after 6 reusability cycles. The weight ratio of SA to ZIF-90 was 0.05 [69].

A calcium-terephthalate metal-organic framework ([Ca(BDC)(H2O)3]) was synthesized in a study using recovered terephthalic acid from waste polyethylene terephthalate (PET) as a precursor. Its ability to adsorb dye Alizarin red S (ARS) from an aqueous solution was examined for the first time. We looked into effective variables including pH, adsorbent dose (m), and starting ARS concentration (C). A proper relationship between the effective variables and either the removal percent (R%) or adsorption capacity (q) response was produced by BBD with 15 runs. For the following ideal conditions: pH = 6, m = 2 mg, and C = 379 mg/L, the suggested BBD model produced a maximum removal percentage (R% = 69.97) and adsorption capacity (q = 788.3 mg/g) of ARS. A Taguchi design with nine runs produced the best results at pH = 5, m = 2, and C = 300 mgL-1. The Langmuir-Freundlich isotherm model well captures the adsorbent-adsorbate behavior since it has the highest nonlinear R2 value (R2 = 0.9966) among the other isotherms. The highest amount of ARS that can be absorbed (qmax) is 979.0 mg/g. The experimental results are consistent with the PSO kinetic model (R2 = 0.9702) [69]. In a separate study, Co- and Ni-MFU-4l, a family of highly selective MOF catalysts for olefin upgrading, were the subject of in-depth X-ray absorption spectroscopy analyses that revealed the mechanisms underlying their deactivation. We further demonstrate that Ni-CFA-1, a more practical and cost-effective substitute for Ni-MFU-4l, replicates both the latter's excellent selectivity and local coordination structure in the ethylene dimerization catalysis. Unmatched in activity, selectivity, and cost among heterogeneous ethylene dimerization catalysts, Ni-CFA-1 activated by MMAO-12 reaches a turnover frequency of 37100 per hour and a selectivity of 87.1% for 1-butene under ideal circumstances. In a one-liter semibatch reactor, Ni-CFA-1 maintains its high activity for at least 12 hours, providing a path toward reliable and scaleable MOFs for industrial catalysis [70].

Metal organic frameworks (MOFs) are unique design platforms for biomimetic catalysts due to their varied chemical and physical properties, but they have had only patchy success thus far due to the instability of the MOFs used in physiological conditions. In this regard, the catalytic production of the bioactive compound nitric oxide (NO) from endogenous sources, S-nitrosothiols, is demonstrated using Cu(II)1,3,5-Benzene-tris-triazole (CuBTTri) (RSNOs). The CuBTTri-poly material retains its catalytic function for the production of NO once it has been prepared, with tunable release kinetics proportional to the total amount of CuBTTri embedded into the polymeric material and a surface flux corresponding to the therapeutic range of 1-100 nm cm2 min1. This function is maintained even after exposure to blood [71].

4.3. Sensing

The majority of modern sensing techniques rely on chromatography, including gas chromatography-mass spectrometry, liquid chromatography-tandem mass spectrometry, and high-performance liquid chromatography, as well as fluorometry, colorimetry, enzyme biosensors, and electrochemical methods [72-78]. These evaluation methods have a number of drawbacks, including time-consuming sample processing, expensive equipment, toxic chemicals, and expensive time-cost. Therefore, there is an urgent need for the expansion of an efficient method for determining various analytes that is accurate, easy, and time-saving [78,79]. Due to Metal-organic frameworks (MOFs) substantial thermal stability, high porosity, and huge surface areas, they have been used as detecting platforms for special analytes such as anions, cations, gases, organic small molecules, explosives, temperature, humidity, and pH, based on the eximious sorption kinetics, reversibility, and guest-induced changes in their structure and/or characteristics [80]. These features make MOFs a promising candidate for sensitive and selective sensors in environmental and industrial applications.

The focus is on optical MOFs because of their aromatic sub-units. Since aromatic linkers emit light [81], many MOFs have been discovered to be photoluminescent. The other type of MOF sensors are based on the powerful photoluminescence characteristics of lanthanide ions (Ln3+), which undergo luminescence variations [82] [83]. Due to the numerous 4f-4f transitions of the lanthanide centers and the clearly defined porosity of the frameworks, lanthanide MOFs, for instance, are discovered to be the ideal option for creating new fluorescence sensors [84]. Ln-doped MOF composites offer a novel class of fluorescence sensor for this purpose, which can detect gases, cations, anions, organic small molecules, humidity, temperature, and pH [85].

By modifying the electrode surface with various hybrid materials (such as functionalized graphene, preanodized/mediator-modified carbon substrates, and Au-based nanomaterials), it is possible to design new electrochemical sensors or biosensors with desirable analytical and electrochemical features to use for standard environmental sensing or biosensing systems [86]. Selecting appropriate materials to combine with the frameworks may be able to overcome the MOFs' large empty volume limitation on conductivity [28].

In order to overcome this obstacle and serve as effective electrochemical sensors for environmental and biological targets, various MOF composite-based platforms have been created [87]. On the other hand, due to their exceptional physicochemical features, noble-metal nanoparticles (NPs) (such as Au, Ag, Pd, and Pt) can be anticipated in sensing, imaging, cancer therapy, optical data storage, and catalysis. However, because of their high surface energy, aggregation limits the aforementioned performances. In order to overcome this difficulty using numerous strategies, the researcher mixes them with MOFs. The resulting composites may be an excellent sensor for different chemical recognition [88,89].

In conclusion, MOF nanocomposites have been exploited for temperature sensing as well as the detection of a number of significant analytes, including heavy metal ions, anions, aromatic hydrocarbons, and hazardous phenolic chemicals. We believe that the knowledge presented in this review about the creation and use of MOF nanocomposites as photoelectrochemical sensors will aid the research teams in developing and establishing more sophisticated MOF-based sensing strategies. However, additional work needs to be done to enhance the MOF nanocomposites' sensing capabilities, particularly with regard to size, shape, design, and the functionalization of MOFs with many molecules by post-synthesis/dopant alterations and entrapment. Functionalized MOFs may also aid in the development of sensitive and selective sensors.

4.4. Water treatment and purification

Numerous methods for the preparation of MOF-based membranes have been developed since the introduction of MOFs to membranes in a variety of industries to improve their overall performance [90,91].

These methods have been applied to enhance the design of MOF-based membranes for liquid separation, especially in the desalination sector employing capacitive deionization [92], adsorption desalination [93], and membrane distillation [94], among others. Accurate and quick water purification depends on the proper design of MOF-based membrane manufacturing techniques. The development of preparation procedures, which have a substantial impact on the configuration of MOF-based membranes and their strength and removal effectiveness, is a significant determinant of the performance of MOF-based FO, RO, NF, and UF membranes in water treatment [92,95].

Although the fundamentals were established in the 1960s, the FO method has lately gained popularity for a variety of applications, most notably saltwater desalination [96]. For application in the water sector, scientists and engineers have looked for innovative methods for creating FO membranes. Although several porous matrix membranes (PMMs) have been employed for NF and UF membranes [91], FO- TFN membranes are less frequently used because of their structural resemblance to porous asymmetric membranes.

For FO applications, it is required to develop a very stable, active, and dense layer on the membrane's top surface in order to get over this restriction. By modifying the conventional dense film-casting method, Arjmandi et al. created a thin-film PMM mixed with magnetic water-unstable MOFs ((magnetic) ZnO@MOF-5) that significantly improved the performance of the FO process [97]. In a different work, a TFN membrane with a suitable 2D MOF (copper 1,4-benzenedicarboxylate) nano-filter in a polyamide active layer was created to improve water flux and antifouling capability without reducing selectivity for FO applications [98]. Controlling the internal concentration polarization is essential for enhancing FO performance. In order to improve the mass transfer efficiency in FO support substrates, Lee et al. used MOFs as a detachable filler to create MOF-based PMMs [99]. They did this by managing the internal concentration polarization (i.e., using lower structural parameter values).

The degree of internal concentration polarization is frequently assessed using the structural parameter. Phase-in-version was used to create porous matrix sub- strates with three distinct types of MOFs by combining MOF particles with a polyacrylonitrile doping solution. The growth of comparatively large macropores inside the PMMs, which increased the mass (water/solute) transfer effectiveness inside the PMM substrate, was the cause of the improved FO performance. Liu et al. created self-standing dense and homogenous UiO-66 nanocomposite thin films (about 400 nm) integrated into polysulfone containing sulfonic functional groups using a straightforward solution casting process and solvent evaporation [100].

It has been widely documented that post-synthesis swapping or strengthening of UiO-66 in various noncovalent bonding forms enhances interfacial interaction with polymers [101,102]. In particular, during the thin-film deposition process, interfacial binding between UiO-66 and the sulfonated polysulfone might develop in thin films in situ. Because of its enhanced compatibility, the UiO-66, a zirconium-based MOF has a conformational reduced flexibility and backbones, increasing the mechanical and structural qualities of thin films strength [92].

4.5. Pharmaceuticals and Biotechnology

It is crucial to take into account a material's function and biocompatibility when using it in biomedical applications, especially those that take place in vivo. Some of the current MOFs might worry about the potential leaching of harmful metal ions or other components in their structure [103,104]. However, a couple of intriguing porous crystals MOFs were used as nontoxic medication delivery systems [105].

They must be built from components that are physiologically and ecologically acceptable for a variety of purposes. For instance, harmless MOFs were obviously preferred over hazardous ones in the majority of biological applications, such as drug delivery systems or intracellular imaging. Recently, researchers looked into the antibacterial activity of MOFs based on nontoxic antimicrobial cations [106,107]. Zinc-based MOFs are being introduced into bioapplication domains, especially as drug carriers, due to the low toxicity of zinc ions. Combining several antibiotic medications and materials allowed researchers to quantify the antibacterial activity [106]. In reality, dermatologists frequently utilized zinc, an endogenous low-toxic transition metal, as a cicatrizing agent, a skin moisturizer, and a combination of anti-dandruff, astringent, anti-inflammatory, and antibacterial agents [108,109]. Zn_2 is typically employed as a connecting point in nonlinear optically active MOFs to prevent undesirable d-d transitions in the visible region.

Recent research (Kitagawa et al. 2004; Rezwan et al. 2006; Ye et al. 2015) have highlighted the potential biological and medical applications of Zn-based MOFs as useful drug delivery vehicles and nontoxic/ biocompatible medicinal agents [110,111]. Drugs could be encapsulated by MOFs and released gradually through their pores [112]. The therapeutic molecule was inserted directly as an organic constituent of the MOF framework in biocompatible drug carriers to prevent side effects [108,113]. Zinc-based MOFs with the aforementioned characteristics, together with low toxicity, biodegradability, and diverse functionality, can be thought of as excellent candidates for creating nanoencapsulators and achieving controlled drug release using cutting-edge delivery methods. According to Bahrani et al., [108], the benign metal Zn and low toxicity linkers carboxylate or phetalat were used to build up the available porosities in these materials.

The nature of host-guest interactions and pore properties have a significant impact on how well drug delivery systems operate in physiological media [114,114].

Deferiprone treatment for hemosiderosis can be seen as a promising ligand in bioactive Zn-based MOFs, as revealed by Burrows et al. [116]. Deferiprone as a chelating agent may be contained in the MOF's trizinc secondary structure before being released into the PBS. As shown by Sun et al. [117], the stiff scaffold provided by the bidentate carbene ligand makes Zn-MOF an effective carrier for the release of cisplatin, an effective anticancer agent with in vitro cytotoxic effects for ovarian cancer cells A2780. This MOF's structure is based on the bridging and chelating ligands 1,4-diazabi-cyclo [2.2.2] octane (DBCO) and 1,4-benzenedicarboxylic acid (H_2bdc), respectively. By using the MTT assay, the IC50 value and cytotoxicity of MOF for human hepatoma cell (HuH_7) were found to be 1.0 mg/mL [108].

4.6. Environmental remediation

For the removal of heavy metals and contaminants from soil and air, MOFs have been proposed. In accordance with the World Water Development Report 2020, 1.6 billion people do not have access to clean water [118]. Additionally, the inclusion of extremely harmful compounds is fast lowering the quality of water supplies. Hazardous substances like dyes, insecticides, phenolics, and chlorinated chemicals are released due to anthropogenic activities like agriculture and industry.

In addition, routine activities have been introducing new pollutants such medications, personal care items, and hormone disrupting substances in minute amounts. The ecosystem may be seriously threatened by these harmful and cancer-causing micropollutants [119,120]. The rising need for fossil fuels like coal, oil, and natural gas is linked to another top-priority environmental concern. Uncontrolled burning of fossil fuels results in the release of harmful and offensive gases, such as volatile organic compounds and volatile sulfur-organic compounds, as well as COx, NOx, and SOx. These gases cause the air quality to significantly deteriorate and are either directly or indirectly related to acid rain and global warming [121,122]. Heterogeneous photocatalysis is a successful method for removing organic pollutants, and semiconductors like TiO_2, ZnO, and ZnS continue to be the most widely used options. Due to their wide band gap energy (Eg * 3.2–3.7 eV) and poor material recovery, these photocatalysts have some important limitations, including limited solar activity [123-125].

As several 3d-block transition metals' oxides and sulfides are known to have small bandgap energies (1.11 eV for $CoFe_2O_4$), they can be used to capture the complete UV-visible spectrum of the sun (Gupta et al. 2020c). As photocatalysts, MOFs with the metal centers Zn(II), Cu(I)/Cu(II), Co(II)/Co(III), and Fe(II)/Fe(III) enable the degradation of organic pollutants under UV/visible light. By transferring charge from the ligand to the metal cluster, the organic linkers in the MOF structure can serve as light "receptionists," activating the transition metal centers.

In photo-redox reactions, the excited MOF can generate electron-hole pairs that can be transported to the surface. The poor coordination of d-block transition metals with ligands in MOFs facilitates the formation of coordination vacancies where the coordinatively unsaturated metal centers act as Lewis acid catalytic sites [126]. Moreover, conjugated organic linkers could be used to adjust the light-harvesting characteristics of these coordinated polymers. The MOFs are regarded as the next generation of photocatalysts since they can utilize the full solar spectrum. Since gas collection and storage was one of MOFs' initial uses, it is possible to employ MOFs as adsor- bents or catalysts to remove harmful gases, which could prove to be an efficient and direct method of reducing the rising level of air pollution.

On the other hand, municipal and industrial wastewaters are disposed of directly into pure water sources without any preparation, thereby introducing a variety of harmful organic compounds. By collecting and decomposing these contaminants into non-toxic chemicals, metal-organic frameworks (MOFs) are gaining attention as a viable alternative to lessen their negative effects on human health. In order to purge organic pollutants, innovative adsorbents and photocatalysts have been developed using these coordination polymers [127]. The most recent reports on MOFs for wastewater treatment, which are mainly concerned with the elimination of organic contaminants, have been provided in the subsections that follow. The efficacy of MOF-based photocatalysts for the degradation of organic colors, medicinal medicines, insecticides, and phenolic compounds is extremely investigated [128,129]. MIL-53(Fe) was reported by Xiang et al. (2017) for the removal of carbamazepine and clofibric acid from deionized water, sewage treatment plants, and river water. Inhibiting metabolism, reproduction, and embryonic development, these substances are medications used to treat excessive blood cholesterol levels and epilepsy, respectively. In 270 minutes, the metal-organic framework (MOF)/H_2O_2/visible system decomposed clofibric acid and carbamazepine, respectively, in 98.2 and 90.1% (deionized water), 94 and 88% (river water), and 71 and 86% (municipal wastewater) [130]. In addition to delayed kinetics and the need for a very low operational pH of 3, the process produced by-products that resembled humic acid and fulvic acid and needed extra treatment to be completely removed from water [130].

The in situ production of reactive species (OH, O^{2-}), which are capable of mineralizing phenolic pollutants even at low concentrations, could be accomplished by heterogeneous photocatalysts using solar energy [131].

The use of metal-organic frameworks (MOFs) as photocatalysts for the degradation of pollutants was first proposed by Garcia's research team [132]. The metal ions in the scaffold are assumed to be responsible for the photocatalytic activity, while the organic linkers operate as light-absorbing chromophores that can gather photons from a wide range of the solar spectrum. When comparing the moles of phenol destroyed per metal ion in the material, MOF-5 displayed comparable photocatalytic activity to commercial TiO_2 P_{25} and ZnO [133].

5. Conclusion and Future Prospects

Significant progress has been made in the introduction of MOFs as effective catalysts for gas separation, medical needs, and as remediation agents for pollution.

The enormous porosity and tunable structure of MOFs enable heavy loadings of biological molecules. But important factors including stability, toxicity, and biocompatibility may limit MOFs' performance in biomedical applications.

The antibacterial activity and biocompatibility of MOFs can be improved, making them a suitable material for medical devices that might greatly enhance healthcare features.

Describe how MOFs can be functionalized and modified with other nanomaterials to improve their separation capabilities, increase their sensitivity, and improve their selectivity when utilized in sensing applications.

The unique property of MOFs, when compared to other cutting-edge materials, is that their separation performances are unaffected by the presence of moisture, strongly indicating their potential for use in practical industrial applications such as water desalination, water purification, and gas storage.

These MOF adsorbents are predicted to play a significant role in the field of CO2 capture if enhanced, as their high stability will improve their resistance to minor components (SOx and NOx) in flue gas as well as decreases in their regeneration energies and enormous synthesis costs.

The availability, affordability, kinetics of toxic gas adsorption/desorption, reusability, and long-term stability of MOFs toward such corrosive gases are significant practical challenges that need to be addressed.

Researchers have created these MOF-based catalysts that work incredibly well in polymerization reactions by utilizing their intrinsic porosity and the ability to synthesize them to create single-site catalysts with clearly defined structural properties.

Due to their relative young within this sub-field, these MOF polymerization catalyst materials have not yet achieved commercialization and use in industrial processes; nonetheless, MOF materials have in general achieved commercialisation. Given the recent commercial success of MOF materials, their potential application has a promising future because they can compete in activity and selectivity with present industrial catalysts.

Future research should examine how the MOF catalyst's physical characteristics vary and what impact those variations have on chemical synthesis of the MOF-based composites using in-situ techniques such as IR spectroscopy, Raman, X-ray absorption and so on.

In the near future, it is strongly advised to understand the catalytic mechanism of MOFs in order to have a clear understanding of how to optimize the reaction parameters and conditions for improved performance in chemical synthesis, including sepration, polymerixation, and biofuel production.

MOFs frequently have drawbacks that restrict their use, such as weak mechanical strength, poor stability, and a single function. Depending on the intended application, combining MOFs with particular materials is strongly advised.

The oxidation of functional groups or metal nodes during the synthesis processes, which can both result in the collapse of the micropores, may cause MOF structures to deteriorate after the compounding process. Such problems may be resolved, at the very least, by optimizing the synthesis settings and conditions or utilizing eco-friendly synthesis techniques.

Additionally, the maximum loading of metal ions in emerging moisture filtering and ion exchange techniques limits the number of NPs in MOF composites. The amount of metal ions loaded for initial wetness filtering depends on the solubility of the precursors in solution and the duration spent immersing the MOF powders, while the maximal loading for an ion-exchange method is determined by the number of active sites in MOFs. As a result, one of the primary difficulties in the synthesis of metal NP/MOF composites is to increase the metalNP loading while preventing their simultaneous aggregation in MOFs.

The production of high-quality MOF-based composites depends on the size, dispersion, and interactions of the MOF particles in the matrix.

The capacity of the membranes to separate will be enhanced by the great homogeneity and dispersion of MOF particles. As a result, there is a considerable demand for MOF particles with surface functionalization and size tuning. However, this research is still in its infancy, so more work needs to be done in the future. The synthesized MOF composites exhibit improved gas absorption, separation, storage capability, and catalytic capabilities thanks to the combination of MOFs and other functional species. Additionally, the interaction of functional elements and matrix materials with MOF structures can expand the uses of MOF composites in new industries including fuel cells, electrical catalysis, and drug delivery and release.

Though it has been asserted that MOFs are stable over a large pH range, there aren't many instances of this, therefore it's impossible to generalize and apply this to all MOFs. Along with the reusability, their durability against oxidants and radiation sources must also be taken into consideration.

A barrier to the commercialization of synthesized nanoscale MOF crystals for wastewater treatment may be the use of hazardous heavy metals (Cd, Cr, and Co), organic linkers (4,4-bipyridine and trimesic acid), solvents (N N-dimethylformamide, chloroform, and acetone), and potential toxicity of the crystals (Kumar et al. 2019).

The price of manufacturing MOFs is another topic that is frequently overlooked in these research studies. It is difficult to evaluate and compare the cost-to-performance ratio with other traditional materials because there is no reliable estimate of the manufacturing cost of MOF.

The least hazardous transition metals, including Fe and Zn, can be given priority, even though it is not possible to limit the amount of organic linkers used in MOF production. Furthermore, by using solvent-free synthesis, hazardous solvents can be completely eliminated. Following alternative solvent-free routes could lower the cost of production because the synthesis of MOF through solvent-free methods like liquid-assisted grinding and aqueous synthesis is comparably less expensive ($13-36 kg-1) than organic solvent (solvothermal) synthesis ($35-71 kg-1) (DeSantis et al. 2017).

The practical application of MOFs necessitates a thorough comprehension of the chemical pathways and their applicability in actual wastewater, both of which should be thoroughly investigated before making any generalizations about their applicability in wastewater treatment facilities.

It is difficult to compare the benefits of adsorption versus catalysis, despite the fact that a small number of papers are devoted to analyzing the reusability difficulties.

MOFs are adaptable catalysts for air purification because they can selectively catalyze the reduction of NO with NH 3 or thermally degrade volatile organic sulfur compounds to produce S 8. Even though MOFs have several advantages for removing gaseous pollutants, they are thermally unstable and start to break down at temperatures as low as 300–400 °C. The thermal stability of MOFs can be improved by increasing the coordination forces with a proper choice of organic linkers and metal nodes.

Additionally, the hydrophilic nature of MOF metal nodes, particularly those that contain transition metals, reduces the active site density and jeopardizes structural integrity through hydrolysis processes. By selecting hydrophobic linkers and grafting oleophilic functions onto the open metal sites, it is possible to create hydrophobic MOFs that will perform better by preventing the entry of water molecules.

Additionally, the MOF stability should be assessed by preserving MOFs in various atmospheric settings to observe how MOFs degrade in the presence of atmospheric oxygen (Du et al. 2019).

Overall, it appears that military applications will more likely lead to MOF commercialization than civilian ones. Every conceivable premise for the commercialization of MOFs is based on their low cost of production, great efficacy, and lack of dependence on secondary chemicals or processes. Therefore, finding inexpensive precursors is crucial for an efficient way to manufacture MOF.

A cost-saving solution could be to locate the least-costly way to produce a MOF instead of using a multi-step procedure.

Another persuasive argument against using MOFs in the wastewater treatment process might be made by doing a more thorough assessment of MOF toxicity to people and other living things. Although the current development of MOFs for environmental applications is constrained by a lack of understanding, MOFs' future importance is very certain. We predict that transition metal-based MOFs will replace current adsorbents and catalysts in commercial air and gas decontamination operations in the next years.

The ability of the synthesis method to be scaled up from an academic/laboratory setting to a big industrial one will determine the future of MOFs. The different factors that should be considered while developing industrial MOF production processes include cost, raw material availability, technical simplicity, yields, purity and quality of synthesized MOFs, and environmental impact. The space-time yield of the synthesis reaction is frequently used to assess the effectiveness of a selected approach. The mass of a MOF produced in one day of synthesis, expressed in kilograms per cubic meter of the reaction mixture, is known as the space-time yield.

For producing MOFs on a wide scale, techniques with high space-time yield values are thought to be the most effective. The literature has discussed the space-time yield values of popular MOFs synthesized utilizing various procedures (Rubio-Martinez et al. 2017). For environmental applications, it makes little sense to produce materials with a high environmental imprint. Because of this, before commercializing the process, factors like environmental footprint should be taken into account in addition to variables like space-time yield.

Commercial MOFs made by Badische Anilin und Soda Fabrik, MOF Apps, and MOF Technologies, including HKUST-1, MOF-5, UiO-66 series, ZIF-67, and ZIF-8, are offered by Sigma-Aldrich (Rubio-Martinez et al. 2017).

The main barrier keeping MOFs from displacing traditional adsorbents in environmental applications is their high cost as of yet. But as the industry develops, new players are joining the market to sell less well-known MOFs, and they'll undoubtedly offer MOFs up to their use in practical environmental applications.

Acknowledgment

The authors received no financial support for the research, author-ship and/or publication of this article.

Conflicts of interest

All authors declare no conflicts of interest in this paper.

REFERENCES

[1] J. Fraden, Handbook of Modern Sensors: Physics, Designs, and Applications, Springer New York2010.

[2] V. Hasija, S. Patial, P. Raizada, A. Aslam Parwaz Khan, A.M. Asiri, Q. Van Le, V.-H. Nguyen, P. Singh, Covalent organic frameworks promoted single metal atom catalysis: Strategies and applications, Coordination Chemistry Reviews 452 (2022) 214298.

[3] A. Kumar, P. Raizada, P. Singh, R.V. Saini, A.K. Saini, A. Hosseini-Bandegharaei, Perspective and status of polymeric graphitic carbon nitride based Z-scheme photocatalytic systems for sustainable photocatalytic water purification, Chemical Engineering Journal 391 (2020) 123496.

[4] H. Meskher, H.C. Mustansar, A.K. Thakur, R. Sathyamurthy, I. Lynch, P. Singh, T.K. Han, R. Saidur, Recent trends in carbon nanotube (CNT)-based biosensors for the fast and sensitive detection of human viruses: a critical review, Nanoscale Advances 5(4) (2023) 992-1010.

[5] W. Ma, B. Yan, Monosystem Discriminative Sensor toward Inorganic Anions via Incorporating Three Different Luminescent Channels in Metal–Organic Frameworks, Analytical Chemistry 94(15) (2022) 5866-5874.

[6] L. Hu, W. Li, L. Wang, B. Wang, Turning metal-organic frameworks into efficient single-atom catalysts via pyrolysis with a focus on oxygen reduction reaction catalysts, EnergyChem 3(3) (2021) 100056.

[7] L. Chen, X. Zhang, X. Cheng, Z. Xie, Q. Kuang, L. Zheng, The function of metal–organic frameworks in the application of MOF-based composites, Nanoscale Advances 2(7) (2020) 2628-2647.

[8] V.F. Yusuf, N.I. Malek, S.K. Kailasa, Review on Metal–Organic Framework Classification, Synthetic Approaches, and Influencing Factors: Applications in Energy, Drug Delivery, and Wastewater Treatment, ACS Omega 7(49) (2022) 44507-44531.

[9] R. Safdar Ali, H. Meng, Z. Li, Zinc-Based Metal-Organic Frameworks in Drug Delivery, Cell Imaging, and Sensing, Molecules 27(1) (2021) 100.

[10] S. Pullen, G.H. Clever, Mixed-Ligand Metal–Organic Frameworks and Heteroleptic Coordination Cages as Multifunctional Scaffolds—A Comparison, Accounts of Chemical Research 51(12) (2018) 3052-3064.

[11] R. Gupta, F. Rahi Alhachami, I. Khalid, H.S. Majdi, N. Nisar, Y. Mohamed Hasan, R. Sivaraman, R.M. Romero Parra, Z.I. Al Mashhadani, Y. Fakri Mustafa, Recent Progress in Aptamer-Functionalized Metal-Organic Frameworks-Based Optical and Electrochemical Sensors for Detection of Mycotoxins, Critical Reviews in Analytical Chemistry (2022) 1-22.

[12] R. Xue, H. Guo, W. Yang, S.-L. Huang, G.-Y. Yang, Cooperation between covalent organic frameworks (COFs) and metal organic frameworks (MOFs): application of COFs-MOFs hybrids, Advanced Composites and Hybrid Materials 5(3) (2022) 1595-1611.

[13] H. Meskher, S.B. Belhaouari, K. Deshmukh, C.M. Hussain, F. Sharifianjazi, A Magnetite Composite of Molecularly Imprinted Polymer and Reduced Graphene Oxide for Sensitive and Selective Electrochemical Detection of Catechol in Water and Milk Samples: An Artificial Neural Network (ANN) Application, Journal of The Electrochemical Society 170(4) (2023) 047502.

[14] H. Meskher, F. Achi, F.B. Moussa, A. Henni, H. Belkhelfa, A Novel Pentachlorophenol Electrochemical Sensor Based on Nickel-Cobalt Layered Double Hydroxide Doped with Reduced Graphene Oxide Composite, ECS Advances 2(1) (2023) 016503.

[15] B. Wang, Z. Zhang, F. Yuan, D. Zhang, Q. Wang, W. Li, Z. Li, Y.A. Wu, W. Wang, An insight into the initial Coulombic efficiency of carbon-based anode materials for potassium-ion batteries, Chemical Engineering Journal 428 (2022) 131093.

[16] A. Zuliani, N. Khiar, C. Carrillo-Carrión, Recent progress of metal–organic frameworks as sensors in (bio)analytical fields: towards real-world applications, Analytical and Bioanalytical Chemistry 415(11) (2023) 2005-2023.

[17] Q. Wang, G. Yang, Y. Fu, N. Li, D. Hao, S. Ma, Nanospace Engineering of Metal-Organic Frameworks for Heterogeneous Catalysis, ChemNanoMat 8(1) (2022) e202100396.

[18] H. Meskher, S.B. Belhaouari, K. Deshmukh, C.M. Hussain, F.J.J.o.T.E.S. Sharifianjazi, A Magnetite Composite of Molecularly Imprinted Polymer and Reduced Graphene Oxide for Sensitive and Selective Electrochemical Detection of Catechol in Water and Milk Samples: An Artificial Neural Network (ANN) Application, 170(4) (2023) 047502.

[19] L. Bazli, M. Bazli, A review on the mechanical properties of synthetic and natural fiber-reinforced polymer composites and their application in the transportation industry, Journal of Composites and Compounds 3(9) (2021) 262-274.

[20] Y. Deng, Y. Wang, X. Xiao, B.J. Saucedo, Z. Zhu, M. Xie, X. Xu, K. Yao, Y. Zhai, Z. Zhang, J. Chen, Progress in Hybridization of Covalent Organic Frameworks and Metal–Organic Frameworks, Small 18(38) (2022) 2202928.

[21] C. Zheng, X. Qiu, J. Han, Y. Wu, S. Liu, Zero-Dimensional-g-CNQD-Coordinated Two-Dimensional Porphyrin MOF Hybrids for Boosting Photocatalytic CO2 Reduction, ACS Applied Materials & Interfaces 11(45) (2019) 42243-42249.

[22] B. Zhang, M. Li, H. Lei, J. Chen, S. Wang, C. Chen, Combining shell confinement and outside decoration to boost the selectivity of Pt nanocatalysts in hollow-flower like Zr-MOFs double shell micro-reactor for hydrogenation cinnamaldehyde to unsaturated alcohol, Applied Surface Science 599 (2022) 153899.

[23] M. Li, S. Qiao, Y. Zheng, Y.H. Andaloussi, X. Li, Z. Zhang, A. Li, P. Cheng, S. Ma, Y. Chen, Fabricating Covalent Organic Framework Capsules with Commodious Microenvironment for Enzymes, Journal of the American Chemical Society 142(14) (2020) 6675-6681.

[24] H. Meskher, T. Ragdi, A.K. Thakur, S. Ha, I. Khelfaoui, R. Sathyamurthy, S.W. Sharshir, A.K. Pandey, R. Saidur, P. Singh, F.S. Jazi, I. Lynch, A Review on CNTs-Based Electrochemical Sensors and Biosensors: Unique Properties and Potential Applications, Critical Reviews in Analytical Chemistry 1-24. (2023).

[25] S. Eskandarinezhad, R. Khosravi, M. Amarzadeh, P. Mondal, F.J.C. Magalhães Filho, Application of different Nanocatalysts in industrial effluent treatment: A review, Journal of Composites and Compounds 3(6) (2021) 43-56.

[26] Y. Qian, F. Zhang, H. Pang, A Review of MOFs and Their Composites-Based Photocatalysts: Synthesis and Applications, Advanced Functional Materials 31(37) (2021) 2104231.

[27] Y. Tao, H.F. Chan, B. Shi, M. Li, K.W. Leong, Light: A Magical Tool for Controlled Drug Delivery, Advanced Functional Materials 30(49) (2020) 2005029.

[28] L. Wang, H. Xu, J. Gao, J. Yao, Q. Zhang, Recent progress in metal-organic frameworks-based hydrogels and aerogels and their applications, Coordination Chemistry Reviews 398 (2019) 213016.

[29] Y. Liu, D. Huang, M. Cheng, Z. Liu, C. Lai, C. Zhang, C. Zhou, W. Xiong, L. Qin, B. Shao, Q. Liang, Metal sulfide/MOF-based composites as visible-light-driven photocatalysts for enhanced hydrogen production from water splitting, Coordination Chemistry Reviews 409 (2020) 213220.

[30] M. Mukoyoshi, H. Kitagawa, Nanoparticle/metal–organic framework hybrid catalysts: elucidating the role of the MOF, Chemical Communications 58(77) (2022) 10757-10767.

[31] H.F. Barton, A.K. Davis, G.N. Parsons, The Effect of Surface Hydroxylation on MOF Formation on ALD Metal Oxides: MOF-525 on TiO2/Polypropylene for Catalytic Hydrolysis of Chemical Warfare Agent Simulants, ACS Applied Materials & Interfaces 12(13) (2020) 14690-14701.

[32] W. Guo, W. Xia, K. Cai, Y. Wu, B. Qiu, Z. Liang, C. Qu, R. Zou, Kinetic-Controlled Formation of Bimetallic Metal–Organic Framework Hybrid Structures, Small 13(41) (2017) 1702049.

[33] M. Samy, M.G. Ibrahim, M. Fujii, K.E. Diab, M. ElKady, M. Gar Alalm, CNTs/MOF-808 painted plates for extended treatment of pharmaceutical and ag-

rochemical wastewaters in a novel photocatalytic reactor, Chemical Engineering Journal 406 (2021) 127152.

[34] S. Mao, X. Cheng, Z. Zhu, Y. Chen, C. Li, M. Zhu, X. Liu, F. Lu, H.-M. Qin, Engineering a thermostable version of D-allulose 3-epimerase from Rhodopirellula baltica via site-directed mutagenesis based on B-factors analysis, Enzyme and Microbial Technology 132 (2020) 109441.

[35] H. Wang, T. Li, J. Li, W. Tong, C. Gao, One-pot synthesis of poly(ethylene glycol) modified zeolitic imidazolate framework-8 nanoparticles: Size control, surface modification and drug encapsulation, Colloids and Surfaces A: Physicochemical and Engineering Aspects 568 (2019) 224-230.

[36] C. Qiao, L. Sun, S. Zhang, P. Liu, L. Chang, C. Zhou, Q. Wei, S. Chen, S. Gao, Pore-size-tuned host–guest interactions in Co-MOFs via in situ microcalorimetry: adsorption and magnetism, Journal of Materials Chemistry C 5(5) (2017) 1064-1073.

[37] Y. Fang, J. Li, T. Togo, F. Jin, Z. Xiao, L. Liu, H. Drake, X. Lian, H.-C. Zhou, Ultra-Small Face-Centered-Cubic Ru Nanoparticles Confined within a Porous Coordination Cage for Dehydrogenation, Chem 4(3) (2018) 555-563.

[38] L. Yang, X. Zeng, W. Wang, D. Cao, Recent Progress in MOF-Derived, Heteroatom-Doped Porous Carbons as Highly Efficient Electrocatalysts for Oxygen Reduction Reaction in Fuel Cells, Advanced Functional Materials 28(7) (2018) 1704537.

[39] W.-w. Zhan, Q. Kuang, J.-z. Zhou, X.-j. Kong, Z.-x. Xie, L.-s. Zheng, Semiconductor@Metal–Organic Framework Core–Shell Heterostructures: A Case of ZnO@ZIF-8 Nanorods with Selective Photoelectrochemical Response, Journal of the American Chemical Society 135(5) (2013) 1926-1933.

[40] Z. Li, R. Yu, J. Huang, Y. Shi, D. Zhang, X. Zhong, D. Wang, Y. Wu, Y. Li, Platinum–nickel frame within metal-organic framework fabricated in situ for hydrogen enrichment and molecular sieving, Nature Communications 6(8248) (2015) 1-8.

[41] V.R. Bakuru, K. Fazl-Ur-Rahman, G. Periyasamy, B. Velaga, N.R. Peela, M.E. Dmello, K.S. Kanakikodi, S.P. Maradur, T.K. Maji, S.B. Kalidindi, Unraveling high alkene selectivity at full conversion in alkyne hydrogenation over Ni under continuous flow conditions, Catalysis Science & Technology 12(17) (2022) 5265-5273.

[42] L.-N. Chen, H.-Q. Li, M.-W. Yan, C.-F. Yuan, W.-W. Zhan, Y.-Q. Jiang, Z.-X. Xie, Q. Kuang, L.-S. Zheng, Ternary Alloys Encapsulated within Different MOFs via a Self-Sacrificing Template Process: A Potential Platform for the Investigation of Size-Selective Catalytic Performances, Small 13(33) (2017) 1700683.

[43] A.E. Espinal, Y. Yan, L. Zhang, L. Espinal, A. Morey, B.O. Wells, M. Aindow, S.L. Suib, Substrate Control of Anisotropic Resistivity in Heteroepitaxial Nanostructured Arrays of Cryptomelane Manganese Oxide on Strontium Titanate, Small 10(1) (2014) 66-72.

[44] W.-T. Koo, S.-J. Kim, J.-S. Jang, D.-H. Kim, I.-D. Kim, Catalytic Metal Nanoparticles Embedded in Conductive Metal–Organic Frameworks for Chemiresistors: Highly Active and Conductive Porous Materials, Advanced Science 6(21) (2019) 1900250.

[45] M.-S. Yao, W.-X. Tang, G.-E. Wang, B. Nath, G. Xu, MOF Thin Film-Coated Metal Oxide Nanowire Array: Significantly Improved Chemiresistor Sensor Performance, Advanced Materials 28(26) (2016) 5229-5234.

[46] J. Zhuang, L.-Y. Chou, B.T. Sneed, Y. Cao, P. Hu, L. Feng, C.-K. Tsung, Surfactant-Mediated Conformal Overgrowth of Core–Shell Metal–Organic Framework Materials with Mismatched Topologies, Small 11(41) (2015) 5551-5555.

[47] L. Chen, W. Zhan, H. Fang, Z. Cao, C. Yuan, Z. Xie, Q. Kuang, L. Zheng, Selective Catalytic Performances of Noble Metal Nanoparticle@MOF Composites: The Concomitant Effect of Aperture Size and Structural Flexibility of MOF Matrices, Chemistry – A European Journal 23(47) (2017) 11397-11403.

[48] M. Zhao, K. Yuan, Y. Wang, G. Li, J. Guo, L. Gu, W. Hu, H. Zhao, Z. Tang, Metal–organic frameworks as selectivity regulators for hydrogenation reactions, Nature 539(7627) (2016) 76-80.

[49] L. He, Y. Liu, J. Liu, Y. Xiong, J. Zheng, Y. Liu, Z. Tang, Core–Shell Noble-Metal@Metal-Organic-Framework Nanoparticles with Highly Selective Sensing Property, Angewandte Chemie International Edition 52(13) (2013) 3741-3745.

[50] H. Liu, L. Chang, L. Chen, Y. Li, In situ one-step synthesis of metal–organic framework encapsulated naked Pt nanoparticles without additional reductants, Journal of Materials Chemistry A 3(15) (2015) 8028-8033.

[51] H. Liu, L. Chang, C. Bai, L. Chen, R. Luque, Y. Li, Controllable Encapsulation of “Clean” Metal Clusters within MOFs through Kinetic Modulation: Towards Advanced Heterogeneous Nanocatalysts, Angewandte Chemie International Edition 55(16) (2016) 5019-5023.

[52] H. Daglar, H.C. Gulbalkan, G. Avci, G.O. Aksu, O.F. Altundal, C. Altintas, I. Erucar, S. Keskin, Effect of Metal–Organic Framework (MOF) Database Selection on the Assessment of Gas Storage and Separation Potentials of MOFs, Angewandte Chemie International Edition 60(14) (2021) 7828-7837.

[53] W. Fan, X. Zhang, Z. Kang, X. Liu, D. Sun, Isoreticular chemistry within metal–organic frameworks for gas storage and separation, Coordination Chemistry Reviews 443 (2021) 213968.

[54] S. Ma, H.-C. Zhou, Gas storage in porous metal–organic frameworks for clean energy applications, Chemical Communications 46(1) (2010) 44-53.

[55] J. Juan-Juan, J.P. Marco-Lozar, F. Suárez-García, D. Cazorla-Amorós, A. Linares-Solano, A comparison of hydrogen storage in activated carbons and a metal–organic framework (MOF-5), Carbon 48(10) (2010) 2906-2909.

[56] W. Fan, X. Liu, X. Wang, Y. Li, C. Xing, Y. Wang, W. Guo, L. Zhang, D. Sun, A fluorine-functionalized microporous In-MOF with high physicochemical stability for light hydrocarbon storage and separation, Inorganic Chemistry Frontiers 5(10) (2018) 2445-2449.

[57] L. Loyon, F. Guiziou, F. Beline, P. Peu, Gaseous Emissions (NH3, N2O, CH4 and CO2) from the aerobic treatment of piggery slurry—Comparison with a conventional storage system, Biosystems Engineering 97(4) (2007) 472-480.

[58] S.L. Swisher, M.C. Lin, A. Liao, E.J. Leeflang, Y. Khan, F.J. Pavinatto, K. Mann, A. Naujokas, D. Young, S. Roy, M.R. Harrison, A.C. Arias, V. Subramanian, M.M. Maharbiz, Impedance sensing device enables early detection of pressure ulcers in vivo, Nature Communications 6(6575) (2015) 1-10.

[59] H. Zhang, Z.G. Wang, Z.N. Zhang, J. Wu, J. Zhang, J.S. He, Regenerated-Cellulose/Multiwalled- Carbon-Nanotube Composite Fibers with Enhanced Mechanical Properties Prepared with the Ionic Liquid 1-Allyl-3-methylimidazolium Chloride, Advanced Materials 19(5) (2007) 698-704.

[60] J. Lei, R. Qian, P. Ling, L. Cui, H. Ju, Design and sensing applications of metal–organic framework composites, TrAC Trends in Analytical Chemistry 58 (2014) 71-78.

[61] C. Petit, Present and future of MOF research in the field of adsorption and molecular separation, Current Opinion in Chemical Engineering 20 (2018) 132-142.

[62] W. Zi, F. Dean Toste, Recent advances in enantioselective gold catalysis, Chemical Society Reviews 45(16) (2016) 4567-4589.

[63] X. Li, X. Yang, H. Xue, H. Pang, Q. Xu, Metal–organic frameworks as a platform for clean energy applications. Energy Chem 2: 100027, 2020.

[64] H. Meskher, T. Ragdi, A.K. Thakur, S. Ha, I. Khelfaoui, R. Sathyamurthy, S.W. Sharshir, A.K. Pandey, R. Saidur, P. Singh, F.S. Jazi, I. Lynch, A Review on CNTs-Based Electrochemical Sensors and Biosensors: Unique Properties and Potential Applications, Critical Reviews in Analytical Chemistry (2023).

[65] H. Meskher, F. Achi, Electrochemical Sensing Systems for the Analysis of Catechol and Hydroquinone in the Aquatic Environments: A Critical Review, Critical Reviews in Analytical Chemistry (2022).

[66] S.-L. Hou, J. Dong, X.-L. Jiang, Z.-H. Jiao, B. Zhao, A Noble-Metal-Free Metal–Organic Framework (MOF) Catalyst for the Highly Efficient Conversion of CO2 with Propargylic Alcohols, Angewandte Chemie International Edition 58(2) (2019) 577-581.

[67] X. Han, W. Zhang, S. Li, C. Cheng, Q. Yu, Q. Jia, L. Zhou, G. Xiu, Mn-MOF derived manganese sulfide as peroxymonosulfate activator for levofloxacin degradation: An electron-transfer dominated and radical/nonradical coupling process, Journal of Environmental Sciences 130 (2023) 197-211.

[68] U. Jamil, A. Husain Khoja, R. Liaquat, S. Raza Naqvi, W. Nor Nadyaini Wan Omar, N. Aishah Saidina Amin, Copper and calcium-based metal organic framework (MOF) catalyst for biodiesel production from waste cooking oil: A process optimization study, Energy Conversion and Management 215 (2020) 112934.

[69] Y. Mao, J. Cheng, H. Guo, Y. Shao, L. Qian, W. Yang, Sulfamic acid–modified zeolitic imidazolate framework (ZIF-90) with synergetic Lewis and Brønsted acid sites for microalgal biodiesel production, Fuel 331 (2023) 125795.

[70] C. Chen, M.R. Alalouni, X. Dong, Z. Cao, Q. Cheng, L. Zheng, L. Meng, C. Guan, L. Liu, E. Abou-Hamad, J. Wang, Z. Shi, K.-W. Huang, L. Cavallo, Y. Han, Highly Active Heterogeneous Catalyst for Ethylene Dimerization Prepared by Selectively Doping Ni on the Surface of a Zeolitic Imidazolate Framework, Journal of the American Chemical Society 143(18) (2021) 7144-7153.

[71] Y. Zhang, Y. Li, W. Liu, Dipole–Dipole and H-Bonding Interactions Significantly Enhance the Multifaceted Mechanical Properties of Thermoresponsive Shape Memory Hydrogels, Advanced Functional Materials 25(3) (2015) 471-480.

[72] H. Meskher, F. Achi, A. Zouaoui, S. Ha, M. Peacock, H. Belkhalfa, Simultaneous and Selective Electrochemical Determination of Catechol and Hydroquinone on A Nickel Oxide (NiO) Reduced Graphene Oxide (rGO) Doped Multiwalled Carbon Nanotube (fMWCNT) Modified Platinum Electrode, Analytical Letters 55(9) (2022) 1466-1481.

[73] M. Hicham, A. Fethi, S. Ha, B. Khaldoun, Antifouling double layers of functionalized-multi-walled carbon nanotubes coated ZnO for sensitive and selective electrochemical detection of catechol, Fullerenes, Nanotubes and Carbon Nanostructures 30(3) (2022) 334-347.

[74] N. Debunne, F. Verbeke, Y. Janssens, E. Wynendaele, B. De Spiegeleer, Chromatography of Quorum Sensing Peptides: An Important Functional Class of the Bacterial Peptidome, Chromatographia 81(1) (2018) 25-40.

[75] N. Kaur, A. Khunger, S.L. Wallen, A. Kaushik, G.R. Chaudhary, R.S. Varma, Advanced green analytical chemistry for environmental pesticide detection, Current Opinion in Green and Sustainable Chemistry 30 (2021) 100488.

[76] Q. Wang, X. Wen, J. Kong, Recent Progress on Uric Acid Detection: A Review, Critical Reviews in Analytical Chemistry 50(4) (2020) 359-375.

[77] A.R. Woldu, Z. Huang, P. Zhao, L. Hu, D. Astruc, Electrochemical CO_2 reduction (CO_2RR) to multi-carbon products over copper-based catalysts, Coordination Chemistry Reviews 454 (2022) 214340.

[78] L. Wang, W. Kong, M. Yang, J. Han, S. Chen, Safety issues and new rapid detection methods in traditional Chinese medicinal materials, Acta Pharmaceutica Sinica B 5(1) (2015) 38-46.

[79] K. Štulı’k, V. Pacáková, M. Tichá, Some potentialities and drawbacks of contemporary size-exclusion chromatography, Journal of Biochemical and Biophysical Methods 56(1) (2003) 1-13.

[80] L. De Smet, G. Vancoillie, P. Minshall, K. Lava, I. Steyaert, E. Schoolaert, E. Van De Walle, P. Dubruel, K. De Clerck, R. Hoogenboom, Plasma dye coating as straightforward and widely applicable procedure for dye immobilization on polymeric materials, Nature Communications 9(1123) (2018) 1-11.

[81] P. Pashazadeh-Panahi, S. Belali, H. Sohrabi, F. Oroojalian, M. Hashemzaei, A. Mokhtarzadeh, M. de la Guardia, Metal-organic frameworks conjugated with biomolecules as efficient platforms for development of biosensors, TrAC Trends in Analytical Chemistry 141 (2021) 116285.

[82] B. Yan, Lanthanide-Functionalized Metal–Organic Framework Hybrid Systems To Create Multiple Luminescent Centers for Chemical Sensing, Accounts of Chemical Research 50(11) (2017) 2789-2798.

[83] Y.-P. Li, X.-H. Zhu, S.-N. Li, Y.-C. Jiang, M.-C. Hu, Q.-G. Zhai, Highly Selective and Sensitive Turn-Off–On Fluorescent Probes for Sensing Al^{3+} Ions Designed by Regulating the Excited-State Intramolecular Proton Transfer Process in Metal–Organic Frameworks, ACS Applied Materials & Interfaces 11(12) (2019) 11338-11348.

[84] T.C. Machado, M.A. Lansarin, C.S. Ribeiro, Wastewater remediation using a spiral shaped reactor for photochemical reduction of hexavalent chromium, Photochemical & Photobiological Sciences 14(3) (2015) 501-505.

[85] Q. Xu, Y. Yang, J. Lu, Y. Lin, S. Feng, X. Luo, D. Di, S. Wang, Q. Zhao, Recent trends of mesoporous silica-based nanoplatforms for nanodynamic therapies, Coordination Chemistry Reviews 469 (2022) 214687.

[86] H. Meskher, F. Achi, S. Ha, B. Berregui, F. Babanini, H. Belkhalfa, Sensitive rGO/MOF based electrochemical sensor for penta-chlorophenol detection: a novel artificial neural network (ANN) application, Sensors & Diagnostics 1(5) (2022) 1032-1043.

[87] S. Kempahanumakkagari, K. Vellingiri, A. Deep, E.E. Kwon, N. Bolan, K.-H. Kim, Metal–organic framework composites as electrocatalysts for electrochemical sensing applications, Coordination Chemistry Reviews 357 (2018) 105-129.

[88] A. Hitabatuma, P. Wang, X. Su, M. Ma, Metal-Organic Frameworks-Based Sensors for Food Safety, Foods 11(3) (2022).

[89] A. Corma, M. Iglesias, F.X.L.i. Xamena, F. Sánchez, Cu and Au Metal–Organic Frameworks Bridge the Gap between Homogeneous and Heterogeneous Catalysts for Alkene Cyclopropanation Reactions, Chemistry – A European Journal 16(32) (2010) 9789-9795.

[90] A. Fethi, M. Hicham, Carbon Electrodes as Emerging Platforms for Miniaturization of Electrochemical Biosensors, Miniaturized Biosensing Devices: Fabrication and Applications, Springer, Singapore, 2022, pp. 39-55.

[91] A. Elrasheedy, N. Nady, M. Bassyouni, A. El-Shazly, Metal Organic Framework Based Polymer Mixed Matrix Membranes: Review on Applications in Water Purification, Membranes 9(7) (2019) 88.

[92] B.-M. Jun, Y.A.J. Al-Hamadani, A. Son, C.M. Park, M. Jang, A. Jang, N.C. Kim, Y. Yoon, Applications of metal-organic framework based membranes in water purification: A review, Separation and Purification Technology 247 (2020) 116947.

[93] E. Elsayed, R. A. L.-Dadah, S. Mahmoud, P. Anderson, A. Elsayed, Experimental testing of aluminium fumarate MOF for adsorption desalination, Desalination 475 (2020) 114170.

[94] S. Daer, J. Kharraz, A. Giwa, S.W. Hasan, Recent applications of nanomaterials in water desalination: A critical review and future opportunities, Desalination 367 (2015) 37-48.

[95] W. Xie, G. Chen, C. Chen, Z. Song, Q. Wu, L. Tian, Z. Dai, S. Liang, P. Tang, X. Zhang, J. Ma, B. Liu, Polydopamine/ polyethyleneimine/ MOF ternary-coated poly (vinyl chloride) nanocomposite membranes based on green solvent for shale gas wastewater treatment, Journal of Membrane Science 665 (2023) 121100.

[96] S.A. Kalogirou, Seawater desalination using renewable energy sources, Progress in Energy and Combustion Science 31(3) (2005) 242-281.

[97] Y. Shang, C. Min, J. Hu, T. Wang, H. Liu, Y. Hu, Synthesis of gold nanoparticles by reduction of HAuCl4 under UV irradiation, Solid State Sciences 15 (2013) 17-23.

[98] K. Sivasankar, K.K. Rani, S.-F. Wang, R. Devasenathipathy, C.-H. Lin, Copper Nanoparticle and Nitrogen Doped Graphite Oxide Based Biosensor for the Sensitive Determination of Glucose, Nanomaterials 8(6) (2018) 429.

[99] J.-Y. Lee, Q. She, F. Huo, C.Y. Tang, Metal–organic framework-based porous matrix membranes for improving mass transfer in forward osmosis membranes, Journal of Membrane Science 492 (2015) 392-399.

[100] H. Liu, M. Cheng, Y. Liu, G. Zhang, L. Li, L. Du, B. Li, S. Xiao, G. Wang, X. Yang, Modified UiO-66 as photocatalysts for boosting the carbon-neutral energy cycle and solving environmental remediation issues, Coordination Chemistry Reviews 458 (2022) 214428.

[101] H. Lian, B. Bao, J. Chen, W. Yang, Y. Yang, R. Hou, S. Ju, Y. Pan, Manipulation strategies for improving gas separation performance on metal-organic frameworks membranes, Results in Engineering 15 (2022) 100609.

[102] A. Tanimu, K. Alhooshani, Insight into the syntheses, performances and mechanisms of organically modified adsorbents for mercury ion sensing and removal, Journal of Environmental Chemical Engineering 9(5) (2021) 105833.

[103] R. Abazari, A.R. Mahjoub, S. Molaie, F. Ghaffarifar, E. Ghasemi, A.M.Z. Slawin, C.L. Carpenter-Warren, The effect of different parameters under ultrasound irradiation for synthesis of new nanostructured Fe_3O_4@bio-MOF as an efficient anti-leishmanial in vitro and in vivo conditions, Ultrasonics Sonochemistry 43 (2018) 248-261.

[104] A.C. McKinlay, R.E. Morris, P. Horcajada, G. Férey, R. Gref, P. Couvreur, C. Serre, BioMOFs: Metal–Organic Frameworks for Biological and Medical Applications, Angewandte Chemie International Edition 49(36) (2010) 6260-6266.

[105] M.-X. Wu, Y.-W. Yang, Metal–Organic Framework (MOF)-Based Drug/Cargo Delivery and Cancer Therapy, Advanced Materials 29(23) (2017) 1606134.

[106] M. Moharramnejad, A. Ehsani, S. Salmani, M. Shahi, R.E. Malekshah, Z.S. Robatjazi, H. Parsimehr, Zinc-based metal-organic frameworks: synthesis and recent progress in biomedical application, Journal of Inorganic and Organometallic Polymers and Materials 32(9) (2022) 3339-3354.

[107] M.N. Hasan, A. Bera, T.K. Maji, S.K. Pal, Sensitization of nontoxic MOF for their potential drug delivery application against microbial infection, Inorganica Chimica Acta 523 (2021) 120381.

[108] S. Bahrani, S.A. Hashemi, S.M. Mousavi, R. Azhdari, Zinc-based metal–organic frameworks as nontoxic and biodegradable platforms for biomedical applications: review study, Drug Metabolism Reviews 51(3) (2019) 356-377.

[109] C. Tamames-Tabar, E. Imbuluzqueta, N. Guillou, C. Serre, S.R. Miller, E. Elkaïm, P. Horcajada, M.J. Blanco-Prieto, A Zn azelate MOF: combining antibacterial effect, CrystEngComm 17(2) (2014) 456-462.

[110] F.J.R. Mejías, S. Trasobares, R.M. Varela, J.M.G. Molinillo, J.J. Calvino, F.A. Macías, One-Step Encapsulation of ortho-Disulfides in Functionalized Zinc MOF. Enabling Metal–Organic Frameworks in Agriculture, ACS Applied Materials & Interfaces 13(7) (2021) 7997-8005.

[111] Y. Wu, Y. Luo, B. Zhou, L. Mei, Q. Wang, B. Zhang, Porous metal-organic framework (MOF) Carrier for incorporation of volatile antimicrobial essential oil, Food Control 98 (2019) 174-178.

[112] S. Mallakpour, E. Nikkhoo, C.M. Hussain, Application of MOF materials as drug delivery systems for cancer therapy and dermal treatment, Coordination Chemistry Reviews 451 (2022) 214262.

[113] W. Cai, C.-C. Chu, G. Liu, Y.-X.J. Wáng, Metal–Organic Framework-Based Nanomedicine Platforms for Drug Delivery and Molecular Imaging, Small 11(37) (2015) 4806-4822.

[114] M.C. Scicluna, L. Vella-Zarb, Evolution of Nanocarrier Drug-Delivery Systems and Recent Advancements in Covalent Organic Framework–Drug Systems, ACS Applied Nano Materials 3(4) (2020) 3097-3115.

[115] M. Kotzabasaki, G.E. Froudakis, Review of computer simulations on anti-cancer drug delivery in MOFs, Inorganic Chemistry Frontiers 5(6) (2018) 1255-1272.

[116] A.D. Burrows, M. Jurcic, L.L. Keenan, R.A. Lane, M.F. Mahon, M.R. Warren, H. Nowell, M. Paradowski, J. Spencer, Incorporation by coordination and release of the iron chelator drug deferiprone from zinc-based metal–organic frameworks, Chemical Communications 49(96) (2013) 11260-11262.

[117] R.W.-Y. Sun, M. Zhang, D. Li, Z.-F. Zhang, H. Cai, M. Li, Y.-J. Xian, S.W. Ng, A.S.-T. Wong, Dinuclear Gold(I) Pyrrolidinedithiocarbamato Complex: Cytotoxic and Antimigratory Activities on Cancer Cells and the Use of Metal–Organic Framework, Chemistry – A European Journal 21(51) (2015) 18534-18538.

[118] W.W. Immerzeel, A.F. Lutz, M. Andrade, A. Bahl, H. Biemans, T. Bolch, S.

Hyde, S. Brumby, B.J. Davies, A.C. Elmore, A. Emmer, M. Feng, A. Fernández, U. Haritashya, J.S. Kargel, M. Koppes, P.D.A. Kraaijenbrink, A.V. Kulkarni, P.A. Mayewski, S. Nepal, P. Pacheco, T.H. Painter, F. Pellicciotti, H. Rajaram, S. Rupper, A. Sinisalo, A.B. Shrestha, D. Viviroli, Y. Wada, C. Xiao, T. Yao, J.E.M. Baillie, Importance and vulnerability of the world's water towers, Nature 577(7790) (2020) 364-369.

[119] W. Liao, Z. Liang, Y. Yu, G. Li, Y. Li, T. An, Pollution profiles, removal performance and health risk reduction of malodorous volatile organic compounds emitted from municipal leachate treating process, Journal of Cleaner Production 315 (2021) 128141.

[120] A.K.C.A. Reis, A. Stern, H.P. Monteiro, S-nitrosothiols and H2S donors: Potential chemo-therapeutic agents in cancer, Redox Biology 27 (2019) 101190.

[121] P.O. Ukaogo, U. Ewuzie, C.V. Onwuka, Environmental pollution: causes, effects, and the remedies, Microorganisms for Sustainable Environment and Health, Elsevier, Walthm, MA, USA, 2020, pp. 419-429.

[122] Z. Liu, Z. Liu, L. Wu, Y. Li, J. Wang, H. Wei, J. Zhang, Effect of polyethylene microplastics and acid rain on the agricultural soil ecosystem in Southern China, Environmental Pollution 303 (2022) 119094.

[123] M. Wen, G. Li, H. Liu, J. Chen, T. An, H. Yamashita, Metal–organic framework-based nanomaterials for adsorption and photocatalytic degradation of gaseous pollutants: recent progress and challenges, Environmental Science: Nano 6(4) (2019) 1006-1025.

[124] R. Ahmad, Z. Ahmad, A.U. Khan, N.R. Mastoi, M. Aslam, J. Kim, Photocatalytic systems as an advanced environmental remediation: Recent developments, limitations and new avenues for applications, Journal of Environmental Chemical Engineering 4(4, Part A) (2016) 4143-4164.

[125] É.N. Santos, Z. László, C. Hodúr, G. Arthanareeswaran, G. Veréb, Photocatalytic membrane filtration and its advantages over conventional approaches in the treatment of oily wastewater: A review, Asia-Pacific Journal of Chemical Engineering 15(5) (2020) e2533.

[126] J. Liu, J. Xue, G.-P. Yang, L.-L. Dang, L.-F. Ma, D.-S. Li, Y.-Y. Wang, Recent advances of functional heterometallic-organic framework (HMOF) materials: Design strategies and applications, Coordination Chemistry Reviews 463 (2022) 214521.

[127] K. Sharma, A. Kumar, T. Ahamad, Q.V. Le, P. Raizada, A. Singh, L.H. Nguyen, S. Thakur, V.-H. Nguyen, P. Singh, Sulphur vacancy defects engineered metal sulfides for amended photo(electro)catalytic water splitting: A review, Journal of Materials Science & Technology 152 (2023) 50-64.

[128] A. Sudhaik, P. Raizada, T. Ahamad, S.M. Alshehri, V.-H. Nguyen, Q. Van Le, S. Thakur, V.K. Thakur, R. Selvasembian, P. Singh, Recent advances in cellulose supported photocatalysis for pollutant mitigation: A review, International Journal of Biological Macromolecules 226 (2023) 1284-1308.

[129] M. Jafarzadeh, Recent Progress in the Development of MOF-Based Photocatalysts for the Photoreduction of Cr(VI), ACS Applied Materials & Interfaces 14(22) (2022) 24993-25024.

[130] Q. Xiang, Z. Yu, P. Wang, N. He, Q. Tan, Q. Wang, X. Xiao, Construction of Z-scheme N-doped $BiFeO_3/NH_2$-MIL-53(Fe) with the synergy of hydrogen peroxide and visible-light-driven photo-Fenton degradation of organic contaminants, Colloids and Surfaces A: Physicochemical and Engineering Aspects 654 (2022) 130112.

[131] C. Yue, L. Chen, H. Zhang, J. Huang, H. Jiang, H. Li, S. Yang, Metal–organic framework-based materials: emerging high-efficiency catalysts for the heterogeneous photocatalytic degradation of pollutants in water, Environmental Science: Water Research & Technology 9(3) (2023) 669-695.

[132] S. Navalón, A. Dhakshinamoorthy, M. Álvaro, B. Ferrer, H. García, Metal–Organic Frameworks as Photocatalysts for Solar-Driven Overall Water Splitting, Chemical Reviews 123(1) (2023) 445-490.

[133] H. Daglar, C. Altintas, I. Erucar, G. Heidari, E.N. Zare, O. Moradi, V. Srivastava, S. Iftekhar, S. Keskin, M. Sillanpää, Metal-organic framework-based materials for the abatement of air pollution and decontamination of wastewater, Chemosphere 303 (2022) 135082.