



Elucidation of synthesis routes and adsorptive mechanisms in removal of water contaminants by MOF-derived carbon materials[☆]

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ABSTRACT

Water contamination has emerged as one of the fundamental factor for water shortage issue in the current era. As of now, different organic and inorganic pollutants are the main toxic components in water and are released from different sources. Metal Organic Frameworks (MOFs) have been developed in different fields because of their novel chemical, catalytic and structural advantages. These materials and their composites have gained much attention in recent years, both as effective sorbents and as photocatalysts, for removing several toxicants such as heavy metals and dyes from the waters and wastewaters. Nowadays, one of extensive research hotspots in these field is MOF derived carbonaceous materials for water detoxification. Among the presently explored materials for water treatment, MOF derived carbons have caused the establishment of great platforms for removal of several contaminations from water, by virtue of their appealing benefits like large pore volume, high porosity, high surface area, and chemical stability. In this review, we focused on different synthesis methods of MOFs and MOFs composites, and furthermore their carbon derived materials were discussed. In addition, applications of MOFs derived carbon materials for water detoxification was thoroughly discussed. More prominently, viewpoints towards exploitation of these developing advanced MOF derived carbon materials as catalytic routes were extensively summarized.

1. Introduction

The current era's rapid population growth and economic expansion have led to higher energy needs, and the use of fossil fuels has brought about serious ecological threats like pollutions, the need for basic necessities, a lack of fresh water sources, and changes to the atmosphere and global health [1,2]. Also, uneven industrial development has led to the deposition of organic and inorganic pollutants into the environment and water bodies, including heavy metals, dyes, pharmaceutical

pollutants, chemical compounds, personal care products, etc., endangering water quality and conceiving the world with an environmental crisis [3–5]. The standard techniques for treating polluted water sources that are now accessible are ineffective against these discharged chemicals, despite the scientists' efforts to address the situation. Typically, these contaminants migrate into surface and ground waters, as well as drinking water sources [6,7]. The high levels of these diffused pollutants will have various unwelcomed effects on humans and other living beings. In addition, volatile organic compounds and toxic gases released

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from industries, agricultural field and domestic regions are also major sources for environmental pollution [8–10], which should be combated by devising novel methods by researchers involved in the related fields. Various methodologies have been proposed for removal of water pollutants that includes physical and chemical techniques, adsorption, separation using biochar and functional materials, immobilization, advanced oxidation process, in-situ microbial remediation techniques, etc. [11–14]. Presently, MOFs (metal organic frameworks) have gained interest among researchers, owing to their advantages, advancements, and wide applications [15–17].

Generally, metal organic frameworks are made of metal clusters or ions that are connected with organic linkers forming one, two or three-dimensional lattices. These porous materials, possessing crystalline structures, are formed through strong bonds with high porosity [18,19]. MOFs can be differentiated based on the metal ions/clusters and organic ligands. Highly porous nature and specific surface area of metal organic framework has extended their applicability in field of environmental remediation, catalytic degradation, biomedical imaging, gas storage, energy production, etc. MOFs possess ability to adsorb various pollutants such as heavy metals, dyes, toxic gases, organic substances, etc., and also they can remove many water contaminants through various processes such as electrochemical processes, photocatalysis, Fenton like oxidation processes, and radical based reactions [20–22]. Past studies have already proved the effective capability of water insoluble MOFs as suitable recyclable material for eliminating pollutants. However, few drawbacks exist such as existence of weak disperse forces due to large availability of void spaces because of their highly porous structure. To overcome the existing drawbacks, studies focused on developing MOF material-based composites like carbon-based MOFs, and MOFs composited with silica, polymers, metal oxides, etc.

Carbon materials generated from metal-organic frameworks (MOFs) have drawn a lot of interest due to their many uses in energy and environmental remediation. High surface area, superior thermal and chemical stability, and adjustable porosity are all features of these materials [23,24]. The carbonization process not only retains some structural features of the original MOFs but also introduces a network of carbon atoms that enhances conductivity, making them suitable for various applications like batteries, supercapacitors, and water treatment processes [25,26]. The incorporation of other materials with MOFs, making composites with some materials like graphene oxide and carbon nanotubes, and transforming the produced composites to carbonized MOFs-based composites can further optimize their properties. This hybridization leads to improved mechanical stability and functional group density, which enhances adsorption capabilities compared to unmodified MOFs. The physical and chemical characteristics of MOF-derived carbons can be customized by using a variety of synthesis techniques, including as post-treatment, co-pyrolysis, and direct carbonization [27]. In water treatment and pollutants removal, the resultant porous carbon composites exhibit excellent performance in adsorption, photocatalysis, and electrocatalysis [25]. More recently, MOF-derived carbon composites have been synthesized with an emphasis on improving structural and functional properties, which has led to increased adsorption efficiency through increased active sites and improved electron transfer which is useful in photocatalysis [28–30]. These developments have established MOF-derived carbonaceous materials as promising materials for sustainable environmental technologies, providing solutions for energy-related applications and water remediation.

In recent years, efficient treatment of waters and wastewaters has been gaining increasing attention, and MOF-based adsorbents are promising solutions for such purposes. In addition to extensive research on using intact MOFs and MOFs-based composites for adsorptive removal of pollutants from aqueous media, some researchers have tried to prepare MOFs-based carbonaceous materials by carbonization of MOFs or MOFs-based composites. The carbonization process leads to production of stable carbonaceous sorbent with improved affinity towards some pollutants. This mini-review highlights the broad

applicability of carbonized metal-organic frameworks (MOFs) materials—both in the form of carbonized pristine MOFs and in the carbonized composite form—in adsorptive removal of pollutants from water and wastewater. The review also elucidates the changes in the adsorptive properties of the carbonized MOF-based materials upon carbonization process, along with the mechanisms by which these materials facilitate pollutant removal, when utilized as adsorbents. This work aims to throw light on the structural and functional properties of these carbonized materials and their potential in water and wastewater treatment purposes, using adsorption technology. Also, at the challenges and the perspectives are discussed.

2. MOF synthesis methods

MOFs are hybrid materials made of inorganic metal linked through organic ligands, possessing large surface area, increased porosity, adaptability, crystallinity and structural flexibility. Various synthesis methods have been proposed so far for producing MOFs with desired characteristics such as surface area, morphology, shape and so on. Eco-friendliness, being biodegradable, green applications, less toxicity, energy efficient and generation of less hazardous secondary products are few key points to be remembered during designing and producing green MOFs [31,32]. A quick rise in number of introduced structures in MOFs shows the remarkable applicability of such materials in various fields. Though MOFs possess numerous advantages, their toxicity, instability, high rate of energy consumption, safety issues, non-biodegradable nature, and poor efficacy constrain the utilization of MOFs to greater extent. Hence, focus must be given more on producing MOFs materials with required qualities for commercialization purposes.

2.1. Materials for MOFs synthesis

2.1.1. Synthesis using solvents

Solvent selection is an important stage in MOFs synthesis process. The main role of solvents is to maintain formation of uniform environment. Hence, solvent selection has significant effect over the structure. Conventional MOFs synthesis involves utilization of organic solvents such as dimethylformamide and diethylformamide. The acidic and basic behaviour of organic solvents have potential effect on analysing the interactions between solute and solvent molecules. Many solvents have high boiling points and low evaporation rate, therefore rate and time of reaction increases [33,34]. MOFs synthesis utilizing solvents results in production of enormous amount of toxic hazardous chemicals during heating process. Fig. 1 shows synthesis of MOFs using various solvents.

On the other hand, green solvents provide less harmful and protective condition for any chemical reaction but are costly. The ecological effect of any solvent can be determined by health impact it causes, nature of degradability and method of extraction. Some solvents can be obtained from any reusable waste material so that toxicity and hazardous effect can be minimized [35]. Green solvents such as dimethyl sulfoxide, methyl or ethyl lactate, ionic liquids, etc. have been utilized for MOFs syntheses. Among the solvents, water is the most inexpensive and convenient liquid for recycling and purification of any material that is produced. Even using green organic solvents have limitations for usage in MOFs synthesis. For instance, organic solvents cannot be used for industrial processes because their handling and controlling require more focus. Present research utilizes water as solvent for MOF synthesis at suitable pressure and temperature. However, drawbacks such as product instability, loss of crystalline nature, etc., must be minimized for using water as solvent. MOFs syntheses using water are high specific possesses and usually need latent heat, resulting in enormous amount of energy loss.

Supercritical liquids are another eco-friendly medium for utilization as solvents. Supercritical water and supercritical carbon dioxide serve as powerful green solvents for MOFs synthesis [36,37]. Supercritical liquids can be produced using various green solvents, owing to their

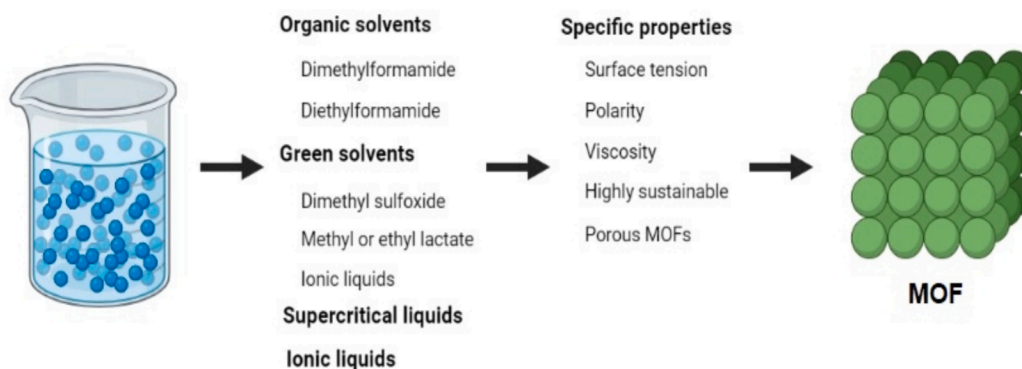


Fig. 1. MOF synthesis using various solvents.

properties such as surface tension, polarity, viscosity, etc. Specific properties of water alter with rising pressure and temperature. Supercritical carbon dioxide also serves as a promising medium and it has a wide applicability in various processes such as extraction, catalytic reactions, polymerization, etc. Supercritical liquids are more suitable for developing highly sustainable and porous MOFs.

Ionic liquids are another emerging medium for replacing chemical and toxic solvents. Ionic liquids are existing in liquid form with organic and inorganic cations and anions [38,39]. Imidazolium, ammonium, are pyridinium are cationic groups while hexafluorophosphate, tetrachloroaluminate, halogen are anionic groups constituting ionic liquids. Ionic liquids possess melting point below that of water and resembles a eco-friendly and sustainable solvent. Ionic liquids consist of pure salts in liquid form at adequate conditions and are held together by electrostatic forces. Low flammability, volatility and vapour pressure of ionic liquids makes these liquids more suitable and convenient for application as solvent [40]. Many research works are effectively utilize ionic liquids as solvents for producing MOFs materials with high stability, recyclability and less volatility. Using ionic liquids, MOFs are synthesised at room temperature or using ionothermal method. Some studies have utilized combination of supercritical carbon dioxide and ionic liquids for MOFs synthesis at standard temperature.

Biomasses are another group of feedstock that can be possess favourable characteristics like chirality, oxygenation, etc. that makes them suitable for producing value added chemicals, and these chemicals can be used for syntheses.

It should be mentioned that utilization of green solvents for synthesis purposes remains challenging. Green solvents offer physico-chemical properties such as polarity, hydrogen bond accepting capability (basic) and donating capability (acidic). Solvent show feasible effect on rate of reaction, steps involved in synthesis process and product selectivity.

2.1.2. Synthesis without solvents

Liquid must be present during MOF synthesis process for speeding the rate of reaction though the liquid and solvent must be selected properly for obtaining crystalline structure. With advancement in research, some synthesis processes have been processed without solvents. For obtaining maximum crystallization and productivity, mechano-synthesis process has been involved, since the secondary product after this process is only water and no other harmful substances are generated. Mechano-synthesis process can be performed by grinding with/without solvents or liquids, grinding using ionic liquids, etc. MOFs synthesised using mechano-chemical methods provides numerous advantages with respect to conversion efficacy, energy, time, etc. [41–43]. This method requires inexpensive metals, hence minimizing the total cost exposed by production process. Commercial preparation of MOF involves mechanical synthesis with high crystalline nature and surface area. Apart from above methods, MOFs are also synthesised using

sonication and microwave energy sources. Microwave methods of crystallizing MOFs are considered to be eco-friendly and sustainable methods of metal and linker assembly. These methods take place in aqueous medium resulting in producing MOFs with large surface area and high yield [44,45]. Compared to available solvent free heating methods, microwave is proved to offer same productivity but does not provide required surface area and crystallinity in the fabricated product. Microwave assisted method can be combined with dry gel method for increasing the efficiency of MOF synthesis. This combination requires less liquid/solvent, energy and minimal reaction time. Proper procedure is to be addressed for light transmission to MOFs for large-scale engineering applications in order to achieve extremely effective light usage, light-responsive desorption, and regeneration of MOF materials. As a result, a single stimulus reaction might lead to less infrastructure volume being used. Adding two or more stimuli to adjust a substance's stimulus release behavior is also an A reaction that happens when reactants are subjected to mechanical energy, like when they are pulverized in a ball mill, is referred to as mechanochemistry. Numerous physical events as well as chemical reactions can be triggered by mechanical forces. In this kind of synthesis, chemical reactions occur after intramolecular connections are ruptured by applied mechanical stress. According to recent research, the use of mechanical force, like in milling or grinding might be wonderful supplement to the more conventional solution-based and solvothermal techniques. The advantages of the mechanochemical technique include rapid product production, large preparation quantities, the use of little solvent or no solvent at room temperature, and promotion of MOF industrialization.

2.1.3. Metal precursors and linkers

Suitable metal precursors that give lesser toxic effects must be chosen while synthesising MOF. Ecological effects of metal and counter ions must be taken into consideration, since hazardous products may cause threat to humans and other living beings [46,47]. Hydroxides, oxides, acetates and carbonates can be utilized as metal precursors along with linkers for synthesising MOFs. Oxides and hydroxides have not been commonly utilized for MOF synthesis, owing to their low solubility. Metal powders can be used as precursors that minimize the safety related issues and productivity problems. MOFs synthesised in industries creates serious disposal problems since degradation may cause metal pollution. Metals such as copper, zinc, nickel, iron, etc. can be used for MOF crystallization [48,49]. Of these metals, zinc and iron were considered to be of the least toxic effect, since these metals are already present in humans' body. But at high concentration, zinc has been found to interfere with cell functioning. Wide research efforts are required in analysing the negative effect of MOFs to humans and environment, as clear information has not been discovered yet.

Linkers also have an important role in examining MOFs structure. Linkers must be chosen selectively and suitably as they determine the functionalities and MOF morphology. Linkers are expensive and their

choice will enormously affect the total expenses of the industrial process. Linker salts also inhibit the mass production of MOF in industries [50,51]. The linker molecules that are used for industrial purposes must produce non-toxic intermediate products or by-products. Imidazoles or carboxylic acids are used as linkers for MOFs synthesis and, unfortunately, they cause release of hazardous secondary products, so anionic forms of linkers are being used for reducing their toxicity. Recently, linker moieties are produced using biomass or waste materials for the process to be green, sustainable, nontoxic, affordable and renewable. Biomolecules such as amino acids, peptides, saccharides, etc. can be used as ligands for synthesising MOFs. These molecules have reactive groups that possess the sites for binding with various metal ion groups [52–54]. MOFs that are synthesised using these biomolecules can be termed as Bio-MOFs and are found to be biocompatible, chiral, and structural diverse and abundance. Nucleobases (purines and pyrimidines) are also used widely as linkers for MOF synthesis owing to their vast availability [55]. Purines (adenine) specifically are more preferred compared to pyrimidine, due to presence of more heteroatoms and hydrogen bonding groups. Peptides, proteins and amino acids are also preferred choice, due to presence of amino and carboxylate groups. Biomolecules can be utilized effectively as ligands for MOF synthesis. Biomolecules containing multiple functional groups suits more for drug delivery purposes. Biomass or waste materials are also recent choice as linkers as they are loaded with carbon content producing various chemical reactions. Utilization of biomass or waste materials will minimize environmental pollution.

2.2. Synthesis methods of MOFs

MOFs can be synthesised using two methods: in-situ (hydrothermal/solvothermal) and ex-situ (mechano-chemical). Of these methods, one-pot solvothermal/hydrothermal method and self-assembly method are commonly used for MOF synthesis particularly for ecological remediation purposes. Fig. 2 demonstrates different methods exploited for MOF synthesis.

2.2.1. Hydrothermal/Solvothermal synthesis method

Both solvothermal and hydrothermal synthesis techniques are essential for creating metal–organic frameworks (MOFs), and each has unique benefits and drawbacks. The hydrothermal technique uses water as the solvent, which enables high-temperature and high-pressure conditions that help dissolve precursors and encourage MOF growth, while the solvothermal technique uses organic solvents, which can improve solubility and control the reaction environment, affecting the size, shape, and crystallinity of the final MOFs. Although the procedural procedures in both methods are similar, the solvent systems used in them vary, which has a big impact on the properties of the materials that are created. A common method involves first dispersing MOF precursors throughout the medium. After that, this mixture is sonicated to help

break up agglomerates and promote uniform dispersion [56,57]. After that, a hydrothermal process is started under carefully monitored circumstances to enable the development of MOFs or MOF-based composites. After centrifugation and thorough washing to remove any remaining chemicals, the final product is obtained by drying. A critical challenge in the synthesis of composites by this method is managing the growth of MOFs on the substrate surface; excessive substrate can lead to defects in the structural integrity of the MOFs. The ability to produce different kinds of MOFs without requiring a lot of resources or complicated purification procedures is what makes this method effective. However, it is important to pay close attention to how much carbon material is added to the reactor because too much can cause unintended chemical reactions that could prevent MOF formation or change their properties. Therefore, it is crucial to optimize the ratio of carbon to MOF precursors in order to achieve desired results in terms of morphology and functionality. This simplified process not only makes synthesis easier but also creates opportunities for the development of advanced materials with specific properties for use in energy storage, environmental remediation, and catalysis.

2.2.2. Self-assembly synthesis method

This method involves direct mixing either by physical forces or chemical interactions, such as hydrogen bonding, electrostatic attractions, etc. MOFs may exhibit positive charges on their surface in acidic or neutral conditions that attracts carbon materials with oxygen functional groups containing negative charges resulting in self-assembled materials [58]. The interactions between MOFs and carbon materials can be facilitated using hydrogen bonding for forming self-assembled structures. Focus must be given on controlling the size and structure of MOFs. Self-assembly method can be used for producing various MOFs for environmental remediation purposes [59].

2.2.3. Sonochemical synthesis method

The word ‘Sono’ denotes ultrasound exploitation and so this process utilizes ultrasound as a heat source, majorly responsible for the reaction to proceed [60]. A mixture containing substrate medium for synthesising MOF is introduced into Pyrex reactor along with sonicator, in absence of cooling agent and with adjustable power supply. Formation and collapse of bubbles (cavitation) takes place after sonication process at high pressure and temperature resulting in rapid heating and cooling [61]. The time required for formation of crystallization and particle size is minimal in this process.

2.2.4. Electrochemical synthesis method

Though numerous methods are available for synthesising MOFs, commercialization is a major issue. Electrochemical method offers solution to this problem through continuous synthesis of MOFs [62]. This method provides more solid content compared to other synthesis procedures. This synthesis method requires cathode plates, an anode and

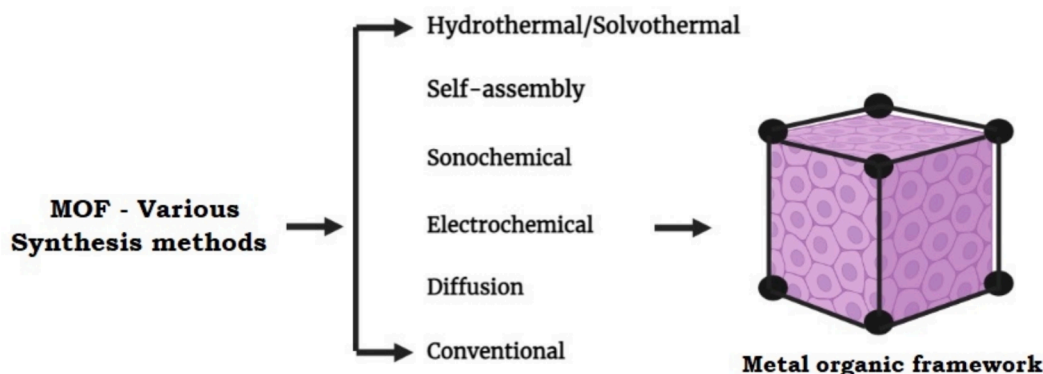


Fig. 2. Different methods for MOF synthesis.

battery. Cathode and anode are immersed in an electrochemical solution containing metal salts and organic ligands. Metal ions are continuously produced through dissolution of anode in the electrochemical medium [63]. Solvents can be used inside the medium for preventing the accumulation of metal ion near the cathode. Hydrogen gas is released during the process. Few important factors that must be measured during the synthesis process include temperature, yield, and texture and current-voltage density. The synthesised MOFs can be characterized using FTIR (Fourier Transform Infrared Spectroscopy), AFM (Atomic Force Microscopy) and XRD (X-ray Diffraction).

2.2.5. Diffusion synthesis method

Liquid phase, gas phase and gel diffusion are included in this method. Solvent is involved in liquid phase diffusion method where metal ions and organic ligands are dissolved. Crystalline MOF are synthesised due to reaction on the surface between organic ligand and metal ions. In gel diffusion method, the metal ions and gel substance are dispersed in solution and mixed at specific time for producing MOF crystals in gel phase while in gas phase volatile ligand solution is utilized as solvent [64]. When reaction takes place between organic ligand and metal ions solution, MOFs are synthesised. Diffusion method can be effectively used for producing MOFs under adequate reaction conditions but time required for synthesis is more which is the major drawback of this process.

2.2.6. Conventional synthesis method

In this method, solvent is used for mixing metal ions, organic ligand and other required materials for specific time period at constant temperature. Then, the product is separated by filtering the reaction mixture for obtaining clear MOF crystals. The crystal size, product morphology and temperature can be controlled while preparing sample. Ceramic based MOFs can be effectively synthesised using this method.

Usually, hydro/solvothermal operations are processed in a specific closed container or high pressurized autoclave underneath sub/supercritical solvent standards. Such mechanisms have aimed on reactant reactivity, synthetic pattern regularity and their association with properties and structures of products [65]. The major dissimilarity among these two relies in reflectivity which is thrown back in their reactive strategies [66]. In hydro/solvothermal reactions, the reactive ions/molecules combine in solution. Anyhow, reaction strategy difference

may tend to several final resultant structures even using same raw materials [67]. Both deals with preparation chemistry, generation and special component assembly via selection path. Non idealistic and non-equilibrium conditions form as key components in both. Water/other solvent systems can be actuated under elevated temperature/pressure states [68]. Hydrothermal operation intrudes water as solvent inherently above boiling ranges. Solvo thermal exercise the process/reactions that intrude non aqueous state solvent under elevated temperature/pressure. Hydrothermal is processed betwixt 100 °C to 500 °C whereas solvothermal at about 1000 °C with > 1 bar pressure. Important solids like zeolites, open-framework compounds, organic-inorganic hybrid materials, metal-organic framework (MOF) materials, superionic conductors, chemical sensors, electronically conducting solids, complex oxide ceramics and fluorides, magnetic materials, and luminescence phosphors have all been successfully prepared using hydrothermal synthesis or solvothermal synthesis (Table 1) [69,70].

Examples: In order to generate Cu-MOFs, an equal volume mixture of copper nitrate in deionized water (solution A) and benzene-1,3,5-tricarboxylic acid (trimesic acid) dissolved in ethanol (solution B) was heated to 383 K for 18 h while being agitated for 30 min. In order to sensitize a doctor-bladed TiO₂ nanoparticle film, which was utilized as a light-absorbing layer in TiO₂-based solar cells, the synthesized Cu-MOFs were applied via a layer-by-layer (LBL) approach to an FTO-coated glass coated with a very thin TiO₂ layer [71].

ZnO was initially grown solvothermally around the close of the 1950 s. In particular, the hydrothermal or solvothermal growth of ZnO has been established in the last 20 years. To produce big, high-quality ZnO single crystals, chemists have created a novel hydrothermal or solvothermal method. High purity and clear ZnO single crystals with a big size of 50 × 50 × 15 mm³ were grown using the hydrothermal approach with a platinum inner container, according to a 2004 study by Ohshima and colleagues. LiOH and KOH are the mineralizers of crystal formation in the experiment. In 2005, Maeda et al. also used the hydrothermal approach in conjunction with an inner container made of platinum to create two-inch ZnO single crystals that were very pure and crystallinity-rich [72].

Cadmium based metal framework and Cu-BTC, respectively, have been formed by combining the modified solvothermal approach encompassing microwave/ultrasonic irradiation for the production of cadmium and copper-based MOFs. The resulting MOFs guaranteed good

Table 1
MOFs derived carbon materials as photocatalysts for photodegradation of toxic contaminants.

S. No	Catalyst/ Synthesis/ Source	Pollutants	Surface area (m ² /g)	Removal rate	Reaction parameters	References
1.	UiO-66-NH ₂ @CNT Hydrothermal Visible light	Methyl orange	1101.1	93 %	pH = 7.0; Time = 30 min; Dye conc = 15 mg/L	[98]
2.	MWCNT@MOF-derived In ₂ S ₃ Solvothermal /Visible light	Tetracycline	--	100 %	Time = 120 min	[99]
3.	carbon dots (CDs)/MIL-88B (Fe)/Bi ₂ S ₃ -Solvothermal/ Visible light	Methylene blue	11.13	60 %	--	[100]
4.	2-N-CQD/MOF-5 - Solvothermal/ Visible light	Cr(VI)	430.7	--	Time = 30 min; Cr(VI) = 50 mg/L	[101]
5.	2 N-CDs@PCN-222@PNIPAM2/ Visible light	Rhodamine B	1497	100 %	Time = 30 min; Pollutant conc = 20 mg/L	[102]
6.	Ho ₂ O ₃ /CNT - Solvothermal/ UV light	Tetracycline	--	98 %	Time = 60 min; Tetracycline conc = 20 mg/L; Temp = 30 °C	[103]
7.	Fe ₃ O ₄ /CuO@C composite - Pyrolysis/ Visible light	Ciprofloxacin	22.06	98.5 %	pH = 7.0; Time = 120 min; CIP conc = 15 mg/L; Catalyst dose = 0.5 g/L	[104]
8.	MOF-derived core/shell C-TiO ₂ /CoTiO ₃ - Direct calcination and solvothermal/ Visible light	Ciprofloxacin	--	99.6 %	Time = 60 min; CIP conc = 10 mg/L	[105]
9.	MIL-53(Fe)/CQDs/MNPs - Two step electrostatic photodeposition/ Visible light	Cr(VI)	--	100 %	Cr(VI) conc = 20 mg/L	[106]
10.	Bi ₂ O ₃ /Bi/PC-900- Hydrothermal/ Visible light	Rhodamine B	354.82	--	Time = 50 min; RhB conc = 10 mg/L; Catalyst dose = 50 mg	[107]
11.	CNTs/MOF-808 Sonication/ Visible light	Diazinon	685.33	97 %	Flow rate = 4 - 8 mL/min; pH = 2.0 - 10.0; Diazinon conc = 10 - 90 mg/L	[108]
12.	Fe-MOF@BiOBr/M - CN Solvothermal/ Visible light	Ciprofloxacin	--	93 %	Time = 120 min	[109]
13.	MOFs-derived Bi ₂ O ₃ @C - Rapid thermal annealing/ Visible light	Tetracycline hydrochloride	--	88 %	Time = 120 min	[110]

thermal stability, and according to analysis, the characterization trends of Cu-BTC showed the formation of crystals (0.2–0.5 μm) with a well-defined porous hexagonal shape. The thickness of the hexagonal crystals was approximately 1 nm, and there were no obvious lattice fringes [73].

2.3. Cost analysis of MOF synthesis

High cost and minimal availability of frameworks are main limitation in the field of MOF synthesis. MOFs are commercialized only in small quantities at high cost that cannot be affordable by researchers or any industrialist for practical applications [74]. For cost analysis on large scale, each single step ought to be considered: solvothermal process, aqueous process and mechano-chemical process. Acting this way is suitable and makes cost estimating convenient for different combination of processes. The total cost required for MOF synthesis is calculated by analysing cost of metal ions, organic ligand, solvent, manufacturing cost, filtration cost, washing, drying, activation and contingency cost. Optimization of process condition and yield and minimizing the cost of metal ions and linkers could cut down the total cost of MOF synthesis. A study showed that by selecting low cost precursor for MOF synthesis, utilizing one-pot in-situ method resulted in production of new MOFs [27,75]. Finally, taking into consideration the cost analyses for old methods and new method for MOF synthesis, it was grasped that it could reduce the total expense for MOF synthesis and make it available commercially without any limitations.

3. MOFs derived carbon materials

Carbon based materials possess high surface area, chemical stability and conductivity, making them promising medium for many remedial applications. These materials have narrow pore distribution and can be linked with heteroatoms such as cobalt, iron, nitrogen, sulphur, phosphorous, etc. that enhances the performance rate during application. Through direct pyrolysis, carbon materials can be produced using MOFs [76–78]. By controlling the temperature during pyrolysis process, pore structural features of MOF precursors can be shifted to carbon materials providing appropriate surface characteristics and structure. These carbon-based materials derived from MOFs have showed potency as emerging and promising porous materials in various realms such as adsorption of ecological pollutants, energy storage, catalyst, energy conversion, etc. Though MOF derived carbon materials possess numerous benefits, few drawbacks elicit some limitations, including the nature of micro-porous structure, metal nanoparticles are not reversible once aggregated, less control during structure formation, etc. Numerous MOF derived materials have been produced with varying structures by optimizing the reaction conditions or structure of precursor materials [79]. Partially synthesised structures can reduce the effect of MOF derived materials during application while regulating the morphology of MOF derived materials results in complete exposure of active sites showing maximum performance.

MOF derived carbon materials may be of hollow, core-shell or fibrous structure. Hollow structure materials have gained interest of many researchers, due to presence of unique cavity like structure that helps the carbon materials to reserve compounds [80]. Hollow structured materials can be synthesised using thermionic method or template method. The core-shell structure is considered to be presiding structure as this structure integrates the benefits of other compounds for enhancing the performance rate. MOF derived carbon materials possessing core shell structure can be produced by alleviating the structure of MOFs precursor and the reaction conditions. Fibrous structure has gradable porous structure with large surface area that helps in complete interactions with active sites exposed [73]. MOF derived carbon materials with fibrous structure can be produced using template method, electrospinning, etc. Apart from these three structures, MOF derived carbon materials can also be found in nanosheets, porous, etc [27,74].

4. Applications of MOFs derived carbon material as adsorbent

MOFs possess unique characteristics such as large surface area and highly porous structure that make them suitable adsorbent material for removal of various organic and inorganic pollutants from water sources [75–77]. This property highly reveals the adsorptive performance of MOFs with their potency to remove many pollutants such as dyes, antibiotics, pesticidal compounds, pharmaceutical products, etc., Table 1 shows that MOFs derived carbon materials as adsorbents for the removal of toxic contaminants [78]. In addition, the chemical and thermal stability of MOFs makes them prominent for functionalization of metal and organic complex, thus increasing their ability to remove various organic pollutants [79–83]. With increasing global water pollution, novel procedures are required for maintaining clean and safe available resources [84,85]. Green MOFs are considered to act as promising adsorbent material for removal of both organic water pollutants (Fig. 3) such as salts, metal ion, etc and inorganic pollutants such as dyes, agrochemicals, oils, pharmaceutical compounds, detergents, hydrocarbons, etc. (Table 2). One major drawback of using MOFs for water remediation purposes is poor stability or instability of MOF to water [86–88]. Carbonations can dispel this drawback wholly or to some degree. Studies proved the efficiency of MOFs as adsorbent material for metal reduction [89–92]. Water filtration is based on the mechanism of reduction and immobilization of reduced pollutants onto the MOF structure. MOFs-based carbons also possess the ability to remove cations and anions from aquatic environment and this has gained attention among researchers. The mechanical stability of MOFs-based carbonaceous materials widens its potency towards various practical applications [94,95,96].

4.1. Dye removal

Dyes cause colour change in water once discharged into water bodies. Reactive dyes are more toxic producing carcinogenic effects in living beings [97,98]. Research is being conducted for analysing the efficacy of MOF-based carbonaceous materials as adsorbents for dye removal from aqueous environment [99]. Parameters such as pore size in parent MOFs, interactions, organic linker functionalization in parent MOFs are reason for removal of dye contaminants by MOF based adsorbent material [101]. These adsorbents are also proved to be efficient against removal of cationic dyes from aqueous medium. For example, removal of methylene blue dye has been studied in past years. Due to electrostatic interactions among MOF-based adsorbent materials and methylene blue dye favoured maximum removal. New approaches are being discovered for improving the adsorptive efficacy of MOF-

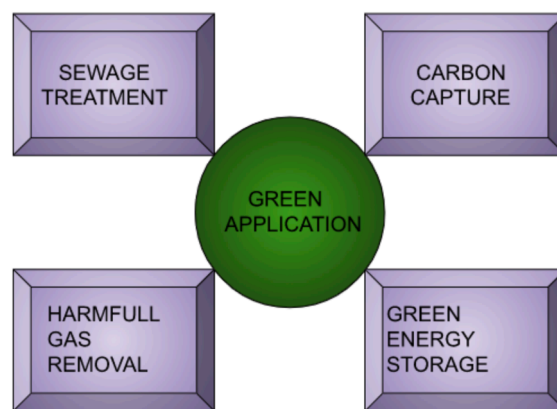


Fig. 3. Green applications of MOF. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2

MOFs derived carbon materials as adsorbents for the removal of toxic contaminants.

S. No	MOF	Synthesis methods	Pollutants	Adsorption capacity (mg/g)	Surface area (m ² /g)	References
1.	Zn-MOF derived graphitic carbon	High-temperature calcination	Ceftazidime	371.18	546.3	[82]
2.	Carbonized Co/Cd-MOF material	Calcination	Moxifloxacin	350.4	12.33	[83]
	Cu/Cu ₂ O/CuO@C	Carbonization	Ciprofloxacin	67.5	~80	[84]
3.	Cu/Cu ₂ O/CuO@C		Tetracycline	112.5	~80	[84]
4.	MnO@C porous nanocomposite	One-step pyrolyzation	Tetracycline	235.6	263	[85]
5.	KOH activated ZIF-L derived N-doped carbon	KOH activation and high-temperature pyrolysis	Tetracycline	330.98	1938.02	[86]
6.	Bio-MOF-1 derived carbon	Carbonization	Bisphenol	5.1 × 10 ²	931	[87]
7.	HKUST-1 derived carbon	High-temperature carbonization	Tetracycline	136.88	4.95	[88]
8.	ZIF-8 pyrolyzed carbon	High-temperature carbonization	sulfamethoxazole	435	1855	[89]
9.	Amino-functionalized MOF-N-NC-800	Carbonization	Methyl orange	222.22	1152	[90]
10.	Carbonized MOF-5	Carbonization	Bisphenol A	757	1731	[91]
11.	Metal-azolate Framework-derived Carbon	Carbonization	Sulfamethoxazole	714	585	[92]
12.	ZIF-67@C-MOF-74	Carbonization	Congo red	180	1210	[93]
13.	MOF-199 derived carbon	Carbonization	Dibenzothiophene	0.059	1876	[94]
14.	Magnetic porous carbon-based sorbent	Pyrolysis	Atrazine	21.753	104	[95]
15.	MOF-74(Zn/Fe)-derived magnetic porous carbon	Calcination	Methylene Blue dye	370	860	[96]
16.	Carbon nanotube-decorated hierarchical porous nickel/carbon hybrid	Carbonization	Methylene Blue dye	686.8	85	[97]
17.	Mg-MOF-74-derived porous MgO/carbon	One-step pyrolyzation	U(VI)	777.51	296.16	[98]
18.	MOF-derived nanoporous carbon	Carbonization	Cu(II)	—	1610	[99]
19.	MOF-NPC	Carbonization	Cu(II)	1071	473	[100]

based carbonaceous materials due to increasing demand for removal of water pollutants and also finding better quality adsorbent materials [100]. Methylene orange dye was also removed efficiently using MOF-based carbonaceous materials similar to methylene blue dye. After in-depth analysis, it was found that interaction between dyes and MOF-based carbonaceous materials during adsorption process is increased by mechanism of adsorption process and factors such as solution pH, dosage of adsorbent material, temperature and organic linker functionalization [102–104]. Though MOF-based carbonaceous materials adsorbent materials show numerous benefits, their incapability of separating mixture of dyes from aqueous medium with similar efficacy remains major drawback. In addition, no proper information is available on disposal of removed dyes after adsorption onto MOF-based carbonaceous materials. However, MOF-based carbonaceous materials showed good regeneration properties while proper disposal of end products after adsorption process is not clearly discovered.

4.2. Removal of antibiotics

Though antibiotics react against microbial infections, they have turned out to be global contaminants due to over disposal. Studies have been preceded for removal of antibiotics from aqueous environment using MOF-based carbonaceous materials. Presence of large surface area on MOFs, adequate interaction among antibiotic compounds and MOF materials, presence of functional groups on MOFs and utilization of derived and magnetic MOFs are the factors identified for effective adsorption of antibiotic compounds by MOF-based carbonaceous materials as adsorbents [83–88]. Magnetic MOF has proved to be effective for antibiotics removal from aqueous solution. In spite of MOF-based carbonaceous materials favourable properties for antibiotics removal, limitations are still present. The more antibiotics are discharged into water bodies, the more microbial resistance genes are being produced. No data is available on MOF limited resistant genes and future research must focus on removal using reactors and water treatment.

4.3. Removal of pharmaceutical and personal care products

Personal care products and pharmaceutical compounds are major group of emerging pollutants owing to their physiological impact on human beings even at minimal doses. Recently these pollutants are in increasing concentration owing to their continuous discharge into

ecosystem and development of analytical methods. The residues of these micropollutants are being found in consuming water sources, wastewater treatment plants and in sewage treatment plants. The metabolites that are excreted after consumption of pharmaceutical compounds get discharged in water bodies causing secondary contamination. Various conventional techniques such as advanced oxidation process, activated sludge process, membrane process, etc. are available for removal of pharmaceutical and personal care products from water sources. Studies also utilized MOF-based carbonaceous materials as alternative materials for adsorptive removal of these pollutants [82] (Table 1).

4.4. Removal of pesticides

Pesticides are group of organochlorine compounds that includes herbicides, fungicides, bactericides, insecticides, etc. Though these compounds possess importance in agricultural field, the impact posed on environment is of major concern when utilized at higher concentration. Hence more research is being conducted on removal of these pollutants using MOF materials. Mechanism of interaction between insecticidal compound and MOF material, presence of large surface area, functional group of surface of MOF and magnetic and derived MOFs are significant factors for pesticidal compounds removal using MOF-based carbonaceous materials [95] (see Table 1). Though studies showed that MOF-based carbonaceous materials have proved to be effective in removal of pesticidal compounds from aqueous solution, no proper information is available on disposal of pesticidal compounds after removal using MOFs and also research is still at laboratory scale due to increased production cost.

5. Mechanism of contaminants detoxification by MOFs and MOFs-based carbons

The removal of toxic contaminants from aqueous streams (Fig. 4) using Metal-Organic Frameworks (MOFs) and related composites involves multiple mechanisms, including π - π interactions, hydrogen bonding, ion exchange, and acid-base interactions [101–103]. Electrostatic inter-linkages are particularly significant as they arise from the interaction between the surface charges of the adsorbates and the oppositely charged MOF carriers, facilitating protonation and deprotonation processes that enhance adsorption efficiency [104]. Additionally, hydrogen linkages formed by interactions among hydrogen ions in

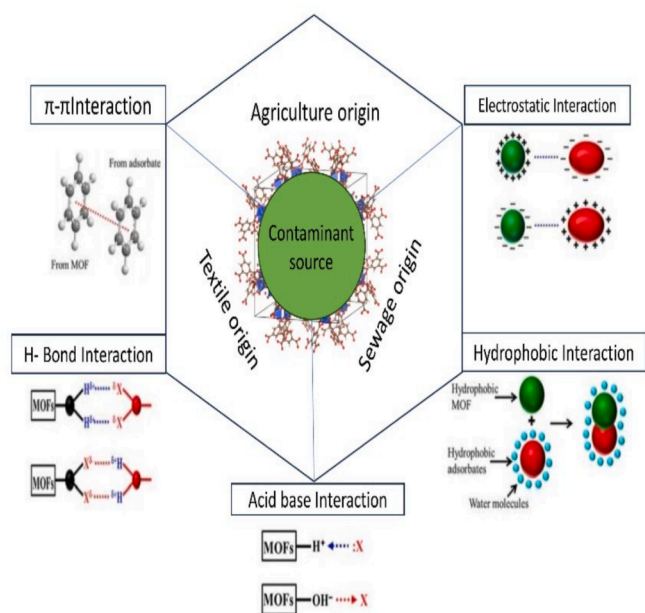


Fig. 4. MOF mechanism with various toxicant sources.

functional groups (like O–H and N–H) contribute to the binding of contaminants to MOFs. Recent studies highlight bi-functional MOF catalysts that exhibit strong affinities for various toxicants from industrial sources [105,106]. When combined with noble metals, these MOFs can also demonstrate superconducting properties, allowing for applications in radioactive metal detection. The adsorption mechanism is predominantly characterized by the binding of pollutants through electrostatic interactions and hydrogen bonding, with acid-base interactions playing a supportive role [107–109]. Hydrophobic interactions can also occur when non-polar groups aggregate in aqueous systems. Furthermore, π - π interactions facilitate the removal of organic pollutants by allowing π systems to engage with anions or metals. The structural orientation of MOFs enables closer connections between toxicants and binding sites, leading to enhanced reactivity and selectivity in pollutant degradation. Overall, MOFs represent a promising approach for wastewater treatment by utilizing their diverse interaction mechanisms to effectively sequester toxic contaminants from agricultural waste streams [110].

Some researchers have elucidated the changes that happens in the functionality and structures the carbonized MOFs and MOFs-based adsorbent, following the transformation of parent materials to carbonaceous materials. For example, Bi et al. reported the transformation of materials from hydrophilic to hydrophobic after calcination, which significantly influences the interactions with adsorbates, particularly in terms of adsorption capacity and dispersibility in

water. The researchers mentioned that this change resulted in an impressive ceftazidime (CAZ) adsorption capacity for the carbonized sorbent. They implied that mechanisms underlying the adsorption of CAZ on the Zn-MOF derived graphitic carbon include molecular size matching selection, hydrophobic effect, and hydrogen bonding. These factors collectively lead to the adsorption effectiveness of CAZ on the hydrophobic graphitic carbon, which are the result of carbonization process [82].

Cheng et al. threw light on the change on the structure of the carbonized product due to the presence of some coordinated ligands. As they mentioned, free water is often not expected to have a major impact on the porosity of the final carbon material during the carbonization process. On the other hand, the elimination of coordinated water molecules is essential for promoting the development of bigger pores and raising pore volume. The significant variations in pore volume between

nickel-carbon (Ni/C) hybrids and carbonized nickel-benzenetricarboxylate (Ni-BTC-O-600) provided as evidence for this phenomena. The increased pore size and volume of Ni/C-600 were favorable to better adsorption capacities for methylene blue (MB) dye, which had a relatively large pore size requirement (more than 2 nm) [97].

The surface area of carbonized MOFs and MOF-based sorbents is not always greater than that of their parent materials. For instance, studies have suggested that the pyrolysis process may have a substantial effect on the specific surface area of the carbonaceous material that is formed, causing it to drop dramatically to little less than 5 m² g⁻¹ [88]. According to Pan et al., there are two main reasons for this decrease: either the organic framework partially collapsed or metals accumulated and blocked the pore structure of MOFs and MOF-based sorbents [87]. These modifications illustrate the intricate relationships that exist between compositional changes and structural integrity during pyrolysis, underscoring the necessity for more research into the underlying mechanisms.

It should be emphasized that the carbonization conditions do have effects on the functionalities of the produced carbon, in addition to the surface area and pore volume. In a study [89], Ahmed et al. indicated that the main way to explain the adsorption behavior of the sulfamethoxazole (SMX) adsorption is by a hydrogen bonding mechanism, in which the metal-organic framework-derived carbon (MDC) surface functional groups operate as hydrogen donors and the sulfamethoxazole (SMX) molecule works as a hydrogen acceptor. The results of these adsorption investigations showed that carbonaceous materials produced by pyrolyzing metal-organic frameworks at ideal temperatures have improved functionalities appropriate for a range of uses. Ahmed et al. indicated that the substance known as MDC-1000 (pyrolyzed at 1000 °C) had a wide variety of acidic functional groups, such as carboxyl (–COOH), lactone, and phenolic (–OH) groups, according to the Boehm titration study. Additionally, MDC-1000's surface was shown to have basic functional groups. Because leftover framework oxygen from the initial metal-organic framework (MOF) influences the oxidation processes that affect the carbon surface, these functionalized surfaces are present [90]. According to earlier research [104,105], the surfaces of oxidized carbon materials usually feature a range of oxygenated functional groups. Interestingly, MDC-1000 exhibits a substantially greater concentration of both acidic and basic functional groups than activated carbon (AC)—more than twice as much as AC [91]. Additionally, the produced substances showed a great deal of promise as adsorbents for the efficient elimination of organic pollutants from aquatic environments.

As with intact metal-organic frameworks (MOFs) and composites based on MOFs, their carbonized counterparts really show notable potential for adsorbing pollutants from aquatic environments as catalytic media (Fig. 5). Numerous processes, including as electrostatic interactions, hydrophobic effects, π - π interactions, hydrogen bonding, acid-base interactions, chemisorption, and pore filling, contribute to this adsorption. These procedures can work separately or together to improve the materials' overall effectiveness in environmental remediation applications [97].

Hydrogen bonding, π - π interactions, and n- π interactions were highlighted in a number of plausible adsorption mechanisms for adsorption of antibiotics, proposed by Tran et al. [77]. The results also showed that the adsorption of ciprofloxacin (CIP) and tetracycline (TTC) followed the pseudo-second order kinetic model, and that this adsorption process was both endothermic and spontaneous, highlighting its thermodynamic favorability [66,117,118].

It is obvious that, dependent on the type of pollutants, their molecular structures, and the solution conditions, the responsible interactions may be different for removal. With a particular emphasis on the impact of pH on the amount of adsorbed bisphenol A (BPA) and the functional groups on biochar-derived carbon (BMDCs) as well as those inherent to the BPA molecule, the study by Bahadra et al. suggests a tenable

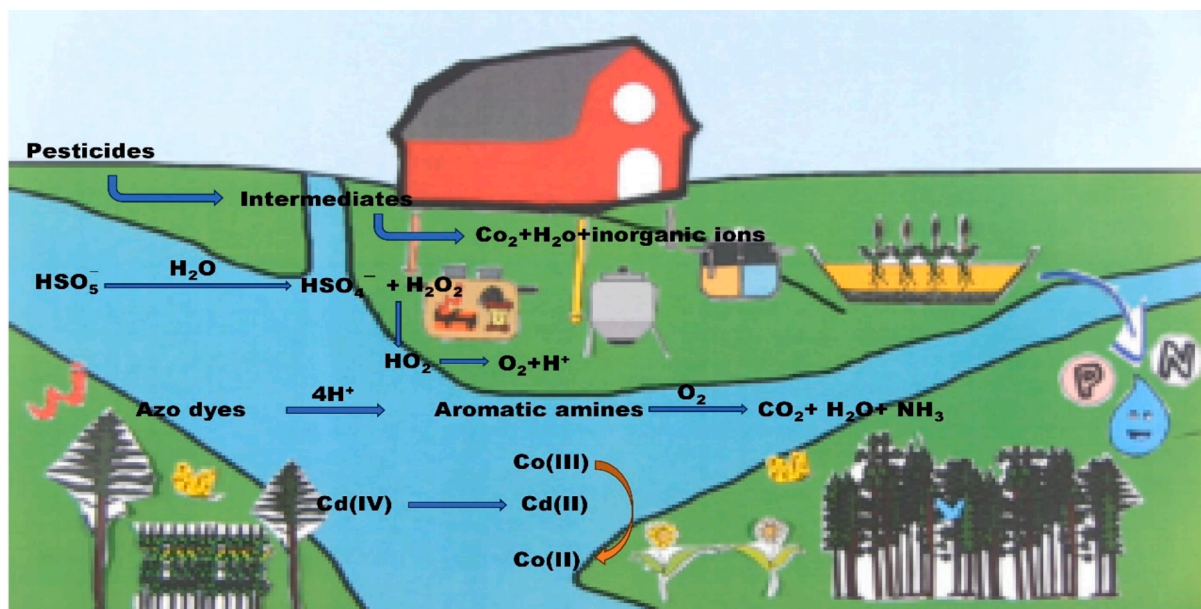


Fig. 5. Catalytic activity of MOF with agricultural contaminants.

explanation for the exceptionally high adsorption capacity of carbonaceous materials. According to the authors, the main mechanism promoting BPA's adsorption onto BMDCs is hydrogen bonding. Furthermore, BPA adsorption is greatly aided by hydrophobic and π - π stacking interactions, especially when the pH is higher than the BPA's acid dissociation constant (pKa). Notably, the work shows that after being used in BPA adsorption, BMDCs may be easily regenerated using solvents to obtain great reusability [87].

At the end, it should be mentioned that the responsible interactions for adsorption of ionic pollutants may be different from those of organic compounds (Fig. 6). For such pollutants, ion-exchange may play an important role in the process. For example, using MOF-derived nanoporous carbon for Cu²⁺ sorption, Bakhtiari et al. mentioned that the -C=O-H and -CO-O-H functional groups act as active sites for the adsorption of Cu²⁺ ions based on the ion-exchange mechanism. By decreasing the H⁺ concentration (increasing pH), the equilibrium shifted to the higher metal ion adsorption [99], because of easier exchange of H⁺ with Cu²⁺ at higher pHs.

6. Stability and recyclability of carbonized MOFs-based materials

When using sorbents for pollution removal, their stability and recyclability are crucial considerations. High surface area, regulated porosity, and superior chemical stability in aqueous conditions are among the special qualities that make carbonized MOFs—also known

as MOF-derived carbon materials, or MDCMs—suitable for environmental applications [111]. Because of these properties, MDCMs may efficiently remove contaminants from water while retaining their structural integrity across several usage cycles. These materials' suitability for commercial use is further increased by their capacity to be regenerated using solvents such as ethanol and methanol, which enables sustainable and reasonably priced pollutant management techniques.

When evaluating the characteristics and reusability of metal-organic frameworks (MOFs) and carbonized MOF materials, characterization approaches are essential. X-ray diffraction (XRD) sheds light on structural integrity and crystallinity. Visual confirmation of morphological alterations is provided by transmission electron microscopy (TEM) and scanning electron microscopy (SEM) [106]. Functional groups and their alterations during adsorption processes are detected using Fourier-transform infrared spectroscopy (FTIR) [100]. Surface area and pore properties are ascertained using nitrogen adsorption-desorption isotherms; argon and CO₂ isotherms are favored for smaller pore sizes. The quality of activation processes is assessed by thermogravimetric analysis (TGA) [107]. These methods, in addition to others like X-ray photoelectron spectroscopy and Raman spectroscopy, offer thorough details on the structure, composition, and performance of MOFs-based sorbents in a range of applications, such as pollutant adsorption and water treatment [108].

The stability and recyclability of carbonized MOFs are critical to their commercial viability in pollution treatment. The need for effective adsorbents is growing as industry look for more environmentally

Influence of framework metal

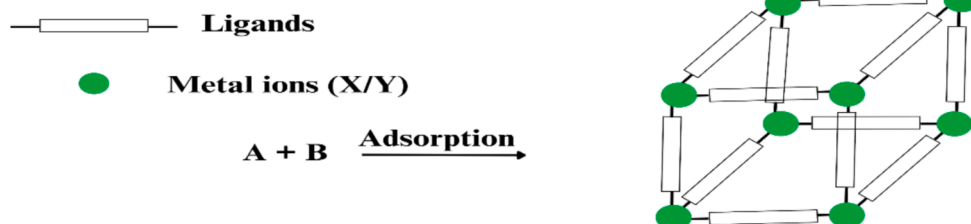


Fig. 6. MOF Adsorptive mechanism.

friendly ways to handle waste and pollutants. MDCMs are excellent candidates for extensive use in industrial processes and water treatment facilities due to their efficient regeneration capability. While investigating new hybrid composites that integrate MOFs with other materials to increase functionality and lower costs, future research should concentrate on refining synthesis techniques to further improve these materials' performance features.

7. Challenges and future perspective in utilizing MOFs for water detoxification

Although there are many opportunities for the use of carbonized MOFs and carbonized MOFs-based composite composites in water treatment, there are a number of issues that need to be resolved in order to improve their effectiveness and commercial viability [112,113]. MOFs are built up using heavier metallic compounds such as chromium, copper, cadmium, pyrazine, etc and there exists chance of release of such toxic contaminants again into environment during MOFs degradation [114]. Not every MOF is made of hazardous materials. A MOF's toxicity is mostly determined by its organic linkers and metal ions [117,118]. For example, metals like iron (Fe), aluminum (Al), and magnesium (Mg), which are frequently utilized in MOFs, show minimal toxicity. Likewise, linkers such as fumaric acid, a food stabilizer, are regarded as safe [115]. Numerous MOFs can be created with non-toxic building blocks, according to a review, highlighting the need of choosing the right parts to guarantee safety [12]. Different varieties of MOFs have varying degrees of recyclability. In some applications, certain MOFs have shown good recyclability. For instance, HKUST-1 and ZIF-8, two deteriorated MOFs, were successfully recycled repeatedly in situ within nanocapsules, according to a study. Over several cycles, these MOFs retained their functionality and structural integrity [116]. However, without more research, these results cannot be applied to all MOFs. In conclusion, MOFs' unique compositions and architectures have a significant impact on both their toxicity and recyclability [112]. The following items include the challenges and perspective which should be kept in view in future studies.

1. The stability of MOFs in water is a major concern because many of them are made of toxic metal compounds that may leak into the environment when they degrade;
2. Maintaining the structural integrity of materials based on carbonized MOFs when exposed to aqueous conditions is crucial to preventing secondary pollution.
3. Creating efficient regeneration methods with environmentally friendly solvents is crucial to raising the materials' affordability.
4. The adsorption processes that remove pollutants are complex and include π - π interactions, hydrogen bonds, electrostatic interactions, etc. The kind of pollutant and the conditions can have a substantial impact on how effective these interactions are. It is still difficult to fully comprehend and optimize these mechanisms for particular contaminants.
5. The adsorption capacity of carbonized MOFs may be impacted by the reduction in surface area and pore volume caused by the carbonization process. According to studies, when certain MOF-based materials undergo pyrolysis, structural collapse or pore blockage can cause a significant decrease in specific surface area. Because of this variability, maintaining high adsorption efficiency requires careful carbonization condition optimization.
6. Although carbonized MOFs have potential, their synthesis can be expensive and energy-intensive. Large-scale applications require the use of more economical and environmentally friendly materials and techniques.
7. Research in the future should concentrate on using green synthesis techniques that use fewer hazardous materials and use less energy. Performance could be maintained while sustainability is

improved by synthesizing MOF-based composites using biomass or biocompatible materials.

8. By functionalizing carbonized MOFs, their surface chemistry can be altered, increasing their pollutant removal efficiency and selectivity. Their applicability in various water treatment scenarios will be improved by customizing the chemical properties to target particular contaminants.
9. Using advanced characterization techniques like Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and X-ray diffraction (XRD) will give more information about the structural integrity and functional characteristics of carbonized MOFs at different phases of pollutant adsorption.
10. Carbonized MOFs' stability and adsorption potential may be improved by combining them with other substances. Better performance metrics in practical applications may result from research into hybrid composites that combine MOFs with other adsorbents, such as activated carbons.
11. Creating legal frameworks that encourage the use of cutting-edge materials like carbonized MOFs will be essential as the need for efficient wastewater treatment solutions increases. This entails evaluating the effects on the environment, making sure everyone is safe, and encouraging sustainable practices in industrial settings.

8. Conclusion

The utilization of carbonized MOFs-based materials for adsorptive removal of water contaminants offers a promising solution to the escalating issue of water pollution. This mini-review highlights the synthesis routes and adsorption mechanisms of MOF-derived carbon materials, emphasizing their interactions with various pollutants. The mechanisms employed by MOFs, such as electrostatic interactions, hydrogen bonding, π - π interactions, acid-base interactions, etc., increase their effectiveness in isolating both organic and inorganic contaminants from water. The adaptability of these materials through carbonization significantly improves their adsorption capabilities, allowing for tailored responses to specific pollutants. Notably, upon carbonization of MOFs-based materials, the transition from hydrophilic to hydrophobic characteristics and other alterations lead to enhanced adsorption capacities for some contaminants. Also, the stability and recyclability of carbonized counterparts in aqueous conditions is another important benefits which is resulted from carbonization. However, challenges remain in optimizing the performance and commercial viability of MOF-base carbonaceous materials. Future research should focus on enhancing the structural integrity of these materials while developing efficient regeneration methods using environmentally friendly solvents. Additionally, understanding complex adsorption processes and optimizing carbonization conditions are vital for maintaining high adsorption efficiency. The synthesis of MOFs via green methodologies that minimize environmental impact is essential for large-scale applications. As industries increasingly seek sustainable wastewater treatment solutions, developing cost-effective, and efficient MOF-based materials will be critical in advancing water remediation technologies. Overall, while MOFs show significant potential for removing toxic contaminants from water sources, carbonization of MOFs-based materials can be a path to address stability, reusability, and environmental safety concerns. Innovations in synthesis techniques and material design are essential for enhancing the practical applicability of MOF-derived carbon materials in sustainable water treatment solutions.

CRedit authorship contribution statement

Sathish Sundararaman: Formal analysis, Data curation. **A. Annam Renita:** Methodology, Investigation. **D. Prabu:** Project administration, Investigation. **J. Aravind Kumar:** Writing – original draft, Data

curation, Conceptualization. **M. Anish:** Validation, Supervision. **J. Jayaprakash:** Visualization, Validation. **R. Thandaiah Prabhu:** Visualization, Validation. **T. Sathish:** Project administration, Formal analysis. **O. Baigenzhonov:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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