frontiers in Materials

TYPE Review
PUBLISHED 08 July 2026
DOI 10.3389/fmats.2026.1865413

Check for updates

OPEN ACCESS

EDITED BY
Maiyong Zhu,
Jiangsu University, China

REVIEWED BY
R. Kamalesh,
Saveetha University, India
Laishi Li,
Shenyang University of Technology, China

*CORRESPONDENCE
Kosar Hikmat Hama Aziz,
kosar.hamaaziz@univsul.edu.iq

RECEIVED 25 April 2026
REVISED 12 June 2026
ACCEPTED 18 June 2026
PUBLISHED 08 July 2026

CITATION
Hama Aziz KH (2026) Metal-organic frameworks (MOFs) based adsorbents for efficient removal of antibiotic pollutants from water.
Front. Mater. 13:1865413.
doi: 10.3389/fmats.2026.1865413

COPYRIGHT
© 2026 Hama Aziz. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Metal-organic frameworks (MOFs) based adsorbents for efficient removal of antibiotic pollutants from water

Kosar Hikmat Hama Aziz*

Department of Chemistry, College of Science, University of Sulaimani, Sulaymaniyah, Iraq

Antibiotics in aquatic environments pose serious risks to ecosystems and human health due to their continuous release from pharmaceutical industries, hospitals, and urban wastewater. Their presence promotes antimicrobial resistance, bioaccumulation, and toxic effects, highlighting the urgent need for efficient and sustainable treatment technologies. Among the available treatment methods, adsorption has emerged as an effective and cost-efficient approach for antibiotic removal due to its simplicity, cost-effectiveness, and applicability in large-scale water treatment systems. Metal-organic frameworks (MOFs) have emerged as promising adsorbents for antibiotic removal due to their high surface area, tunable porosity, abundant active sites, and versatile structures. This review discusses the synthesis, modification, adsorption mechanisms, and performance of MOF-based adsorbents for antibiotic removal from water. The effects of key operational parameters and the major challenges related to regeneration, stability, scalability, and practical application are critically evaluated. In addition, recent advances in MOF-based multifunctional materials and integrated adsorption–degradation systems are highlighted for their enhanced treatment efficiency. Finally, future perspectives are proposed to support the development of sustainable and high-performance MOF-based adsorbents for water treatment applications.

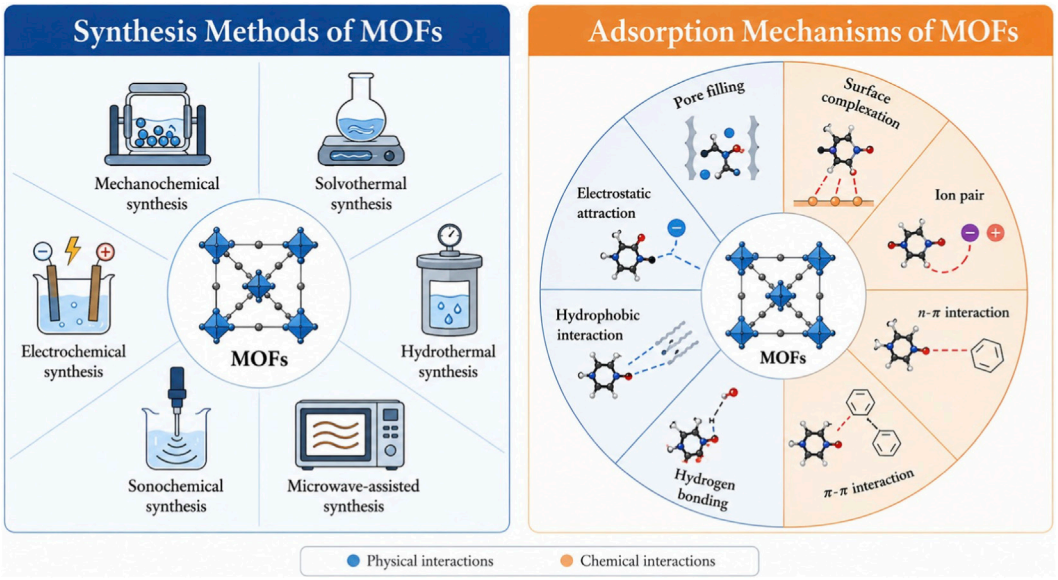
KEYWORDS
adsorption, antibiotic pollutants, bioaccumulation, MOFs, wastewater treatment

Highlights

- MOFs as adsorbents for antibiotic removal from water are critically reviewed.
- Sources of antibiotic water pollution and related health risks are highlighted.
- Synthesis methods and modification strategies of MOFs are summarized.
- Adsorption mechanisms of MOFs for antibiotic removal are discussed.
- Research gaps and future directions in advanced MOF engineering are proposed.

1 Introduction

Rapid industrialization, urbanization, and increased production of goods have significantly increased the complexity of organic pollutants in wastewater, with many newly identified compounds recognized as toxic and potentially carcinogenic in aquatic



GRAPHICAL ABSTRACT

environments (Chandel et al., 2026; Worku et al., 2025). Antibiotics are biologically active organic compounds extensively used in human healthcare, veterinary medicine, animal husbandry, agriculture, and aquaculture to prevent and treat microbial infections. Based on their origin and production pathway, antibiotics are commonly classified into natural, semisynthetic, and synthetic categories (Browne et al., 2023; Okeke et al., 2022). The extensive use and uncontrolled release of antibiotics have led to their persistent occurrence in aquatic and terrestrial environments, where they are recognized as emerging contaminants of major environmental concern. A significant proportion of administered antibiotics is excreted unchanged or as active metabolites, ultimately entering wastewater treatment systems that often fail to ensure their complete removal (Zhang et al., 2024). The excessive and uncontrolled use of antibiotics has reduced their therapeutic efficacy against bacterial pathogens, accelerating antimicrobial resistance and increasing the demand for novel and more effective antimicrobial agents (Karki et al., 2026). The persistence of antibiotic residues in environmental matrices can induce adverse ecotoxicological effects, alter microbial community dynamics, and threaten aquatic ecosystems even at trace concentrations (Bilal et al., 2020). Moreover, the continuous environmental exposure to antibiotics imposes selective pressure on microorganisms, thereby accelerating the propagation of antibiotic-resistant bacteria and resistance genes. This phenomenon further diminishes antimicrobial efficacy and promotes the emergence of multidrug-resistant pathogens, posing severe risks to environmental and public health (Wu Z. et al., 2025; Chen et al., 2026). Therefore, the development of efficient and sustainable treatment technologies for the removal of antibiotics prior to their discharge into aquatic environments is of critical importance, particularly for effluents originating from pharmaceutical industries, hospitals, agricultural activities, livestock farms, urban wastewater systems, and veterinary sectors.

Several methods have been applied for the removal of antibiotics from water, including membrane filtration (Liu H. et al., 2023), adsorption (Mangla et al., 2022), advanced oxidation processes (AOPs) (Anjali and Shanthakumar, 2019), and biodegradation (Han et al., 2020), which are among the most used water treatment technologies today. Biodegradation, using plants and microorganisms, is an environmentally friendly approach; however, most antibiotics are persistent and non-biodegradable. In addition, this method typically requires large land areas, which limits its practical applicability. AOPs are highly effective for antibiotic removal, enabling degradation and mineralization via *in situ* generation of reactive species such as hydroxyl (•OH) and sulfate ($SO_4^{\bullet-}$) radicals, as well as singlet oxygen ($^1O_2$) (Hama Aziz et al., 2025). However, their application is often limited by operational complexity, strict pH requirements, and high costs at large scale. Moreover, some systems (e.g., Fenton- and persulfate-based AOPs) require chemical inputs and may generate significant sludge, while their efficiency can decline at trace pollutant concentrations (Hu et al., 2025; Hama et al., 2025). Membrane filtration is also an efficient separation technique; however, membrane fouling and the need for frequent maintenance increase operational costs and limit long-term performance (Buakaew and Ratanatamskul, 2026). Adsorption is a well-established, Adsorption is a well-established, cost-effective, and highly efficient water purification method for the removal of a wide range of contaminants of environmental and public health concern, including antibiotics. Owing to its low cost, operational simplicity, versatility, flexibility, and ease of regeneration, together with its high removal efficiency, adsorption has emerged as a highly competitive and promising alternative to conventional treatment processes (Hemavathy et al., 2026; Kamalesh and Saravanan, 2026). The performance of an adsorbent is influenced by surface area, porosity, availability of active sites, and the interactions with target pollutants (Al-Ghouti and Da'ana, 2020; Nasar, 2026).

Due to its operational simplicity, ease of regeneration, economic feasibility, and high removal efficiency even at low contaminant concentrations, adsorption is widely recognized as one of the most promising methods for practical environmental applications. However, conventional adsorbents such as activated carbon, zeolites, ion exchange resins, and clay minerals often exhibit inherent limitations, including limited adsorption capacity, poor selectivity, and challenges associated with regeneration. Therefore, the development of advanced adsorbent materials with high efficiency, stability, and long-term reusability has emerged as a major research focus in environmental remediation, particularly for the removal of emerging organic pollutants such as antibiotics.

A variety of conventional and advanced adsorbents have been developed for the efficient removal of antibiotics from water, including biochar, carbon nanotubes, metallic nanoparticles, chitosan, cellulose derivatives, polymers and bio-based composites, MXenes, MOFs, and their composites. Moreover, organic wastes from municipal, industrial, and agricultural sources can be valorized as sustainable feedstocks for producing low-cost adsorbents, enhancing the sustainability of water treatment processes (Mancuso et al., 2026; Zu et al., 2025; Poomipuen et al., 2026; Mirizadeh et al., 2026; Yan et al., 2026; Qian et al., 2026; Saravanan et al., 2023). Among them, MOFs have emerged as a new class of highly efficient and stable adsorbents, characterized by well-defined crystalline structures, high porosity, and tunable pore sizes, which enable effective removal of antibiotics from aqueous solutions (Zheng et al., 2025; RR et al., 2026). The application of MOFs in water treatment has grown substantially in recent years, highlighting their exceptional structural tunability and multifunctional performance. MOFs are crystalline porous materials formed via the self-assembly of metal ions or metal clusters with organic linkers, yielding highly ordered frameworks with well-defined and adjustable pore structures (Kamalesh et al., 2026). They have been effectively utilized for the adsorption and removal of a broad range of contaminants, including toxic heavy metal ions and emerging antibiotic pollutants (Li et al., 2025a; Mei et al., 2025). Although several reviews have discussed MOF-based adsorbents for water treatment and antibiotic removal, limited attention has been given to the relationships between adsorption mechanisms, different antibiotics, operational parameters, sustainable synthesis strategies, and practical application challenges (Ha et al., 2026; Am et al., 2026; Mubarak, 2026). Recent review articles have extensively summarized the application of MOFs and MOF-based nanocomposites for antibiotic removal, particularly regarding adsorption performance, material design, and remediation efficiency (Yang et al., 2022; Shah et al., 2024; Thakur and Bharti, 2025). However, a more integrated and updated discussion addressing adsorption mechanisms, antibiotic characteristics, regeneration behavior, sustainable synthesis approaches, scalability, and practical wastewater treatment challenges remain necessary. Therefore, this review comprehensively evaluates recent advances in MOF-based adsorbents for antibiotic removal from water, with emphasis on MOF synthesis and modification strategies, adsorption mechanisms, performance optimization, multifunctional materials, and practical limitations related to regeneration, stability, and real wastewater applications. In addition, recent progress in green synthesis and waste-to-value approaches utilizing agro-industrial residues for MOF fabrication is critically discussed, together with future perspectives for developing sustainable and high-performance MOF-based adsorbents.

2 Antibiotics in aquatic systems: sources and health risks

Antibiotics are a class of chemical compounds, either naturally derived from microorganisms such as bacteria or synthetically produced, that inhibit the growth of or eliminate pathogenic bacteria. They are widely used to treat infections in humans and animals caused by both Gram-positive and Gram-negative bacteria. Representative compounds, including tetracycline, oxytetracycline, chlortetracycline, and doxycycline, were introduced in the late 1940s (Deng et al., 2025; Sardar et al., 2026). Antibiotic contamination in aquatic environments promotes the emergence of resistant pathogenic genotypes, leading to infections that are increasingly difficult to treat and associated with higher morbidity and mortality (Okeke et al., 2025). A significant fraction of administered antibiotics is excreted in urine and feces and subsequently enters effluents from domestic sewage, wastewater treatment plants, hospitals, and livestock operations due to incomplete metabolism in humans and animals (Karki et al., 2026). Additional inputs arise from wastewater irrigation and the application of animal manure and sewage sludge. Inadequate treatment processes and improper disposal practices further contribute to the persistence of antibiotics in the environment (Fakorede et al., 2026). The increasing concentration of antibiotics in aquatic environments has become a significant environmental and public health concern. This trend is primarily driven by their extensive use in human and veterinary medicine, hospitals, aquaculture, pharmaceutical manufacturing, and other industrial activities (Yuan et al., 2025; Kawsar et al., 2026). Although these contaminants are typically detected in surface waters at low concentrations, generally ranging from ng/L to μg/L. Over time, excessive water use combined with antibiotic contamination can intensify the ecotoxicological impacts of these compounds due to their persistence and cumulative effects in receiving environments (Nassri et al., 2023). Global antibiotic consumption has increased markedly over recent decades, rising from approximately 21.1 thousand tons in 2000 to about 34.8 thousand tons in 2015. According to the World Health Organization Global Antimicrobial Resistance Monitoring System, antibiotic-resistant infections are responsible for an estimated 700,000 deaths annually worldwide (Bai et al., 2026). Consequently, sustainable water management becomes increasingly challenging, particularly under the pressures of population growth and climate change. As illustrated in Figure 1, antibiotics originating from hospitals, pharmaceutical industries, residential activities, and agricultural practices are continuously introduced into aquatic environments through wastewater discharge, surface runoff, and improper disposal. The widespread occurrence of commonly used antibiotics, such as tetracycline, oxytetracycline, ciprofloxacin, levofloxacin, and enrofloxacin, has raised significant environmental and public health concerns due to their persistence, bioaccumulation potential, toxicity, and possible carcinogenic effects. The continuous release and accumulation of these contaminants in water systems highlight the urgent need for effective and sustainable remediation technologies for antibiotic removal.

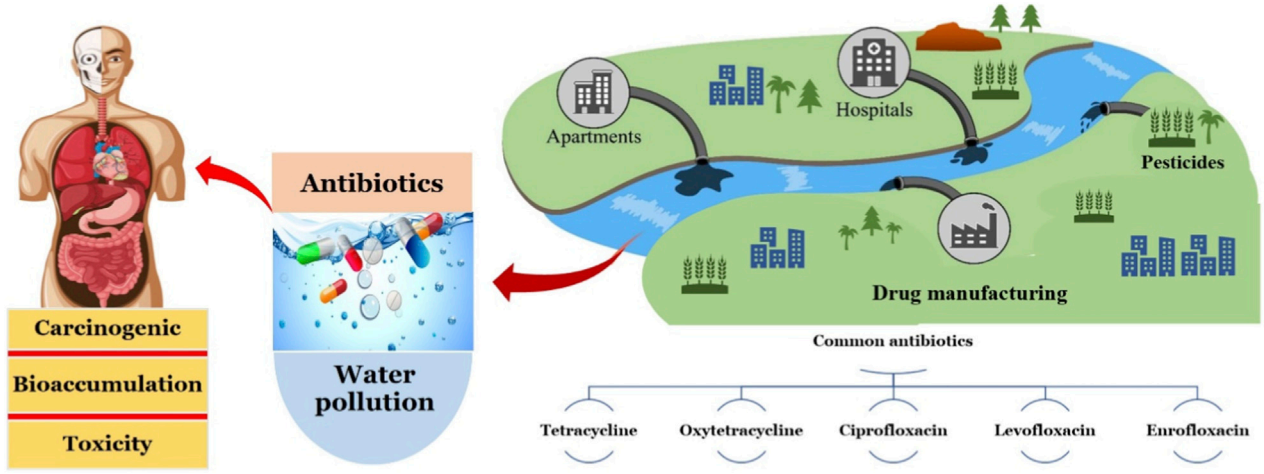


FIGURE 1
Antibiotic sources in water and human health risks.

3 Synthesis and modification of MOFs

The synthesis and properties of MOFs are strongly influenced by the selection of metal nodes, organic linkers, solvents, and reaction conditions, enabling the design of engineered architectures with high surface area, tunable porosity, and diverse functionalities (Ahmed et al., 2026). As illustrated in Figure 2, various synthesis approaches, including solvothermal, hydrothermal, mechanochemical, electrochemical, sonochemical, and microwave-assisted methods, have been widely employed for MOF fabrication. These synthesis strategies significantly affect the structural characteristics, stability, and adsorption performance of MOFs for antibiotic removal from aqueous systems. Typically, MOF formation follows a multistep pathway involving coordination bond formation, nucleation, and crystal growth. In the initial stage, metal ions or clusters coordinate with organic linkers, establishing the primary structural framework of the material (Yi et al., 2026; Han et al., 2025). The solvothermal synthesis of MOFs was first reported in 1995 and remains one of the most widely used and effective methods for gram-scale production in laboratories worldwide. This approach involves dissolving metal salts and organic linkers in an appropriate solvent, followed by controlled heating to induce crystallization and form an extended, insoluble, and structurally stable MOF framework. Commonly used high-boiling solvents include dimethyl sulfoxide (DMSO), N,N-dimethylformamide (DMF), N,N-diethylformamide (DEF), and N,N-dimethylacetamide (DMA), which facilitate controlled crystal growth. When water is employed as the reaction medium, the process is referred to as hydrothermal synthesis (Yi et al., 2026; Kukkar and Kukkar, 2025). Electrochemical production of MOFs offers an efficient alternative to conventional solvothermal methods, based on *in situ* generation of metal ions via an applied electric current instead of pre-formed metal salts. This approach enables continuous production under mild conditions, with significantly faster kinetics, reducing crystallization time (Aziz et al., 2025a). Crystal growth can be precisely controlled by tuning electrochemical parameters. It is particularly suitable for producing uniform thin films and coatings at ambient condition. In addition, nitrate counterion recycling enhances the environmental sustainability of the process. Microwave-assisted MOF synthesis is based on rapid volumetric dielectric heating, in which the reaction mixture directly absorbs microwave energy (Chakhtouna et al., 2023). This induces rapid supersaturation and burst nucleation of MOF crystals, followed by a self-limiting growth stage due to rapid depletion of precursors. As a result, small, uniform, and phase-pure crystals are formed in significantly shorter reaction times compared with conventional synthesis methods (Gao et al., 2024). Mechanochemistry involves solid-state reactions initiated by grinding or milling of reactants to enhance contact and reactivity. It can be performed manually using a mortar and pestle or via mechanical milling systems such as ball mills. The applied mechanical energy induces localized heating, particle size reduction, defect formation, and, in some cases, phase transitions, while also improving mass transfer through continuous exposure of fresh surfaces (Marrett et al., 2025). Reaction efficiency depends on parameters such as milling time, rate of heating, speed rotation, and applied pressure. Compared with manual grinding, mechanized milling offers higher energy input, improved reproducibility, and better control, making it more suitable for systematic and scalable synthesis. Ultrasound-assisted MOF synthesis is driven by acoustic cavitation within an ultrasonic bath reactor, where the formation and collapse of microbubbles generate localized high temperature and pressure, thereby facilitating the formation of metal–ligand coordination bonds (Liu H-X. et al., 2023). These conditions enhance mass transfer between transition metal ions and organic linkers, promoting rapid nucleation and framework formation. As a result, highly crystalline MOFs with reduced particle size and narrow size distribution are produced within significantly shorter reaction times, often under ambient conditions compared with conventional methods (Weng et al., 2026). Different synthesis methods significantly influence crystalline, porosity, morphology, stability, and adsorption efficiency of MOFs for antibiotic removal. Conventional methods such as solvothermal and hydrothermal synthesis generally produce highly crystalline and stable MOFs but

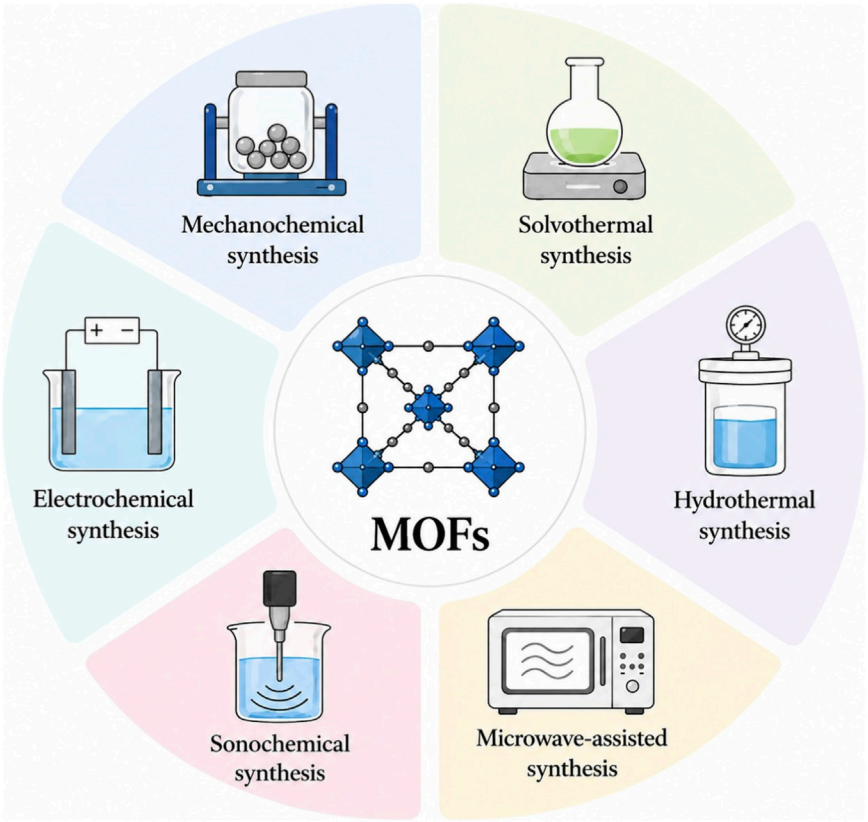


FIGURE 2
Typical methods used for MOF synthesis.

often require long reaction times and high energy consumption. In contrast, microwave-assisted, sonochemical, mechanochemical, and electrochemical methods offer rapid synthesis, lower solvent consumption, and improved control over particle size and surface properties. Each approach presents specific advantages in terms of reaction kinetics, crystal size control, energy efficiency, and environmental considerations. Therefore, the selection of a suitable synthesis method mainly depends on the desired structural properties, scalability requirements, and intended application of the MOF material. A comparative overview of the major MOF synthesis methods and their influence on antibiotic adsorption performance is summarized in Table 1.

In addition to conventional synthesis approaches, increasing attention has been directed toward advanced post-synthetic and *in situ* modification strategies for MOFs. These approaches enable precise control over pore environments, surface chemistry, and active sites, thereby significantly enhancing the performance of engineered MOFs in targeted applications such as adsorption and catalysis (Iqbal A. et al., 2025; Abazari et al., 2019). Moreover, emerging synthesis techniques have been developed to improve the structural tunability, scalability, and sustainability of MOF production. Continuous flow synthesis offers efficient and reproducible large-scale fabrication, while spray-drying and template-assisted methods enable better control over particle morphology and hierarchical porosity (Wang et al., 2022; Senthil Raja and Tsai, 2024). In addition, green synthesis approaches employing environmentally benign solvents and biomass-derived precursors have attracted growing interest due to their reduced environmental impact. More recently, machine learning-assisted and AI-driven strategies have emerged as promising tools for accelerating MOF design and optimizing synthesis conditions for enhanced material performance (Ma et al., 2026). Despite the significant advances achieved through post-synthetic modification, defect engineering, and composite fabrication, current developments remain largely centered on material-level optimization. In contrast, comprehensive system-level integration involving adsorption, desorption, and resource recovery processes remain insufficiently investigated, particularly with respect to reactor configuration, dynamic operational conditions, process scalability, and lifecycle assessment. Defect engineering highlights a key methodological limitation, as the creation of additional active sites is often not accompanied by consideration of their impact on structural stability (Fang et al., 2015). Excessive defect density may accelerate framework hydrolysis during regeneration, thereby compromising the structural stability and long-term durability of MOFs. Consequently, materials with enhanced adsorption capacity but limited stability may reduce overall process efficiency and economic feasibility. Therefore, the selection of appropriate MOF modification strategies should consider the nature of target antibiotic pollutants, environmental conditions, operational requirements, and cost-effectiveness. A systematic evaluation and comparison of these approaches is essential to

TABLE 1 Comparison of major MOF synthesis methods and their influence on antibiotic adsorption performance (Maleki et al., 2024; Duo et al., 2023; Sutherland, 2025).

Synthesis method	Advantages	Limitations	Adsorption performance
Solvothermal	High crystallinity and porosity	Long reaction time and high energy consumption	Enhances adsorption capacity through well-developed pore structures
Hydrothermal	Good water stability and structural integrity	Requires high temperature and pressure	Improves adsorption stability in aqueous systems
Microwave-assisted	Rapid and energy-efficient synthesis	Possible non-uniform crystal growth	Accelerates adsorption kinetics due to smaller particle size
Sonochemical	Fast nucleation and high surface area	Limited scalability	Increases active adsorption sites
Mechanochemical	Low-solvent and eco-friendly process	Lower crystallinity in some cases	Promotes defect-rich adsorption sites
Electrochemical	Controlled synthesis under mild conditions	Limited scalability	Enables tunable surface properties for adsorption

guide material selection and inform future research directions. The selection of appropriate MOF design strategies requires a holistic balance between performance, cost, stability, and environmental impact. Although functionalized and composite MOFs often exhibit enhanced performance, their increased complexity may restrict practical deployment. Future research should therefore prioritize simplified and cost-effective design strategies that retain high efficiency while improving feasibility for real-world applications.

4 Regeneration, reusability, and stability of MOFs

The regeneration, reusability, and stability of MOFs are critical factors determining their practical applicability in antibiotic adsorption from aqueous environments. In addition to achieving high adsorption capacity, an ideal MOF-based adsorbent should maintain its structural integrity, adsorption efficiency, and physicochemical properties after multiple adsorption-desorption cycles. The regeneration performance of MOFs is strongly influenced by several factors, including framework stability, desorption methods, pore structure, and the nature of interactions between antibiotics and active adsorption sites. Furthermore, the chemical and water stability of MOFs remain major challenges for their long-term application, particularly under complex environmental conditions. Therefore, understanding the stability and recyclability of MOFs is essential for evaluating their economic feasibility, environmental sustainability, and potential for large-scale wastewater treatment applications. The integration of MOFs with advanced oxidation processes (AOPs) can improve MOF reusability by degrading adsorbed antibiotics through *in situ* generated reactive species, thereby regenerating active adsorption sites (Aziz et al., 2025b). Nevertheless, maintaining MOF structural stability during regeneration remains a critical challenge, as reactive species may simultaneously induce framework degradation. In some cases, however, enhanced performance after initial cycles has been observed due to the formation of additional active sites and increased porosity resulting from redox-induced surface modifications. To enhance MOF stability, the incorporation of hydrophobic and soft nitrogen-donor ligands coordinated with divalent metal ions has emerged as an effective strategy (Bosch et al., 2014). According to the hard-soft acid-base theory, highly stable MOFs can be rationally designed through the coordination of acids and bases with similar hardness characteristics. Strong coordination interactions between hard acids and hard bases (e.g., carboxylates with Al^{3+}, Fe^{3+}, Cr^{3+}, Ti^{4+}, or Zr^{4+}) or soft acids and soft bases (e.g., azoate or pyrazolate ligands with Zn^{2+}, Cu^{2+}, Ni^{2+}, or Mn^{2+}) significantly enhance the hydrolytic and water stability of MOF structures (Shen et al., 2024).

Common regeneration solvents for MOFs after antibiotic adsorption include methanol, ethanol, acetone, deionized water, and dilute acidic or alkaline solutions (Sutherland, 2025). Among these, methanol and ethanol are the most widely used because they effectively desorb antibiotic molecules while preserving the structural stability of the MOF framework. In some cases, NaCl, NaOH or HCl solutions are employed to enhance desorption efficiency through pH adjustment and surface charge modification. The selection of an appropriate regeneration solvent plays a critical role in determining the recyclability, structural stability, and adsorption efficiency of MOFs during repeated adsorption-desorption cycles, which is essential for their practical implementation in wastewater treatment applications. Other regeneration strategies include microbiological, electrochemical, ultrasonic, and wet air oxidation methods (Ahmed et al., 2015). When solvent-based regeneration is applied, the amount of solvent used should be minimized to reduce operational costs and environmental impact compared with conventional water-intensive regeneration processes. Table 2 summarizes the major regeneration solvents and agents used for MOF-based adsorbents in antibiotic removal. Various regeneration strategies, including organic solvent washing, pH-assisted desorption, oxidative treatment, and thermal regeneration, have been investigated to restore adsorption capacity and improve MOF reusability. However, regeneration conditions should be carefully optimized to maintain the structural stability and long-term performance of MOFs during repeated adsorption-desorption cycles. Organic solvents, particularly acetone, methanol, and ethanol, are commonly used for the regeneration and desorption of antibiotics from MOFs owing to

TABLE 2 Regeneration methods and solvents used for MOF-based antibiotic adsorbents.

MOFs	Antibiotics	Regeneration method/Solvent	Advantages	Ref.
NH2-MIL-101(Fe)	Tetracycline	Ultrasonication, water and methanol	Low-cost and stable over three cycles	Dong et al. (2020)
MIL-101(Fe)	Levofloxacin	Ethanol-water mixture	Safe, cost-effective, stable over four cycles	Chaturvedi et al. (2020)
Mn-UiO-66	Tetracycline	NaOH followed by DMF sonication	Stable up to the third cycle	Yang et al. (2019)
Ni@Zn-MOF	Norfloxacin	0.1M NaOH	Efficiency remained at 60% after five cycles	Li et al. (2025b)
K-CIA@MOF-808	Tetracycline	Ethanol	85% capacity retained after 5 cycles	Gul et al. (2026)
Zn/Mn-MOFs/GO	Minocycline	DMF	84% capacity retained after 3 cycles	Ren et al. (2026)
Pd-MOF)/chitosan-cellulose	Ciprofloxacin	Ethanol and 0.1 N HCl (7:3, v/v)	83% capacity retained after 5 cycles	Ben Hamadi et al. (2026)
Magnetic Sn-MOF	Amoxicillin	NaOH/HCl followed by ethanol	92% capacity retained after 6 cycles	Alshammari et al. (2024)

their high solvation capability and strong affinity toward antibiotic molecules (Zhou et al., 2020). Acidic and alkaline solutions, such as HCl and NaOH, are also widely used as effective eluents because they modify the surface charge of the adsorbent, thereby weakening the electrostatic interactions between the adsorbent and antibiotic molecules (Mahmoud et al., 2020).

5 Mechanisms of antibiotic adsorption by MOFs

MOFs have been effectively utilized for the adsorption of antibiotics from aqueous systems. This process is inherently complex and is influenced by the interplay between the structural properties of the MOFs and the physicochemical characteristics of the antibiotic molecules (Pooresmaeil and Namazi, 2026; Mirsoleimani-azizi et al., 2018; Abbasnia et al., 2022; Weng et al., 2025). These interactions can be broadly classified into physisorption and chemisorption, as shown in Figure 3. Physical adsorption is driven by weak, reversible interactions without electron transfer or bond formation. π–π interactions result from the overlap between the aromatic rings of antibiotics such as tetracycline and the graphitic domains of MOFs (Wu J. et al., 2025). Owing to the high surface area and tunable porosity of MOFs, pore filling is a key mechanism, where antibiotic molecules smaller than the pore size are trapped within internal cavities via van der Waals forces. Such interactions are most effective when antibiotics like tetracycline remain in a neutral form, as electrostatic influences are minimized, allowing π–π stacking to control adsorption behavior (Mahmoud et al., 2024). Electrostatic attraction depends on MOF surface charge and antibiotic ionization, both of which are pH-dependent, enabling interactions between oppositely charged species under suitable conditions (Karthik et al., 2025). Under acidic conditions, negatively charged MOF surfaces enhance the adsorption of cationic antibiotic species through electrostatic attraction. In contrast, alkaline conditions may promote electrostatic repulsion, unless compensated by other interaction mechanisms. Additionally, ionic strength and the presence of competing ions can significantly affect these interactions by compressing the double layer of electrical energy and reducing the overall electrostatic attraction (Qin et al., 2022). Hydrophobic interactions contribute notably for antibiotics containing aromatic or aliphatic moieties, which preferentially partition into hydrophobic MOF frameworks in aqueous media (El-Sawaf et al., 2026). H-bonding also occurs between functional groups on MOF ligands (e.g., -OH, -NH_2, and -COOH groups) and electronegative sites in antibiotic molecules such as sulfonamides and tetracyclines (Zhang et al., 2022). These interactions play a significant role in adsorption, particularly in MOFs rich in surface functional groups. The strength of H-bonding is strongly influenced by pH, as variations in pH alter the protonation and deprotonation states of these groups, thereby affecting their bonding capacity. Overall, these weak interactions are reversible, facilitating efficient regeneration and reuse of MOFs, which is essential for large-scale applications. Chemical adsorption involves stronger and more specific interactions, typically resulting in higher selectivity and adsorption capacity. Many antibiotics contain aromatic structures that enable π–π stacking with the delocalized π-electron systems of MOF organic linkers. In addition, n–π interactions may occur when lone pair electrons from heteroatoms such as nitrogen or oxygen in antibiotics interact with π-electron-deficient aromatic rings of the MOF framework (Liu et al., 2019). Surface complexation can also take place through coordination between antibiotic functional groups and exposed metal sites or unsaturated metal nodes, often serving as a dominant mechanism for antibiotics with strong chelating ability (Aziz et al., 2025b). Surface complexation involves the formation of inner- or outer-sphere complexes between antibiotic molecules and functional groups on the MOF surface. Oxygen-containing groups, such as carboxyl and hydroxyl moieties, can establish strong interactions with antibiotics, particularly under favorable pH conditions. These interactions are often characteristic of chemisorption, resulting in enhanced adsorption stability and reduced desorption compared to physical adsorption, which may limit the ease of adsorbent regeneration (Liu L. et al., 2020). Furthermore, oppositely charged antibiotics and MOF surfaces may form stable ion pairs, particularly in ionic frameworks or MOFs modified with ionic liquids. These mechanisms generally operate synergistically rather than independently, and their efficiency is strongly influenced by aqueous environmental conditions. Parameters such as ionic strength, dissolved organic matter, and temperature can significantly enhance or suppress adsorption

kinetics and capacity (Sompornpailin et al., 2021; Mirsoleimani-azizi et al., 2018). A comprehensive understanding of molecular-level adsorption interactions is essential for the rational design of MOFs with high selectivity and adsorption efficiency toward specific antibiotic classes. The adsorption behavior of antibiotics on MOFs is governed not only by general interactions such as pore filling, electrostatic attraction, hydrogen bonding, π–π stacking, hydrophobic interactions, ion pairing, and surface complexation, but also by the intrinsic structural characteristics of the MOFs, including metal nodes, organic linkers, pore size distribution, surface area, functional groups, defect density, and surface charge (Batool et al., 2026). Variations in these physicochemical properties strongly influence adsorption affinity, accessibility of active sites, and adsorption kinetics. For instance, MOFs containing unsaturated metal centers or oxygen-containing functional groups can enhance coordination interactions and H-bonding with polar antibiotic molecules, whereas aromatic linkers promote π–π interactions with antibiotics containing conjugated ring structures (Yusuf et al., 2026). Similarly, hierarchical porosity and defect-rich structures improve mass transfer and provide additional adsorption sites, thereby enhancing uptake capacity. The adsorption performance is also highly dependent on the physicochemical properties and speciation behavior of antibiotics in aqueous media (Hu and Huang, 2026). Since most antibiotics are amphoteric compounds with multiple pKa values, their charge state changes with solution pH, which directly affects electrostatic interactions with MOF surfaces (Park et al., 2025). Therefore, the relationship between solution pH, antibiotic ionization, and MOF surface charge, commonly evaluated through zeta potential analysis, plays a critical role in determining adsorption efficiency and selectivity. At pH values below the point of zero charge, positively charged MOF surfaces may favor adsorption of anionic antibiotic species, whereas negatively charged surfaces at higher pH conditions enhance the uptake of cationic antibiotics. In addition, coexisting ions and natural organic matter in real wastewater matrices may compete for active sites, block pores, or alter surface charge, thereby reducing adsorption performance and modifying the dominant adsorption pathway (Zou et al., 2026).

Mechanistic elucidation generally requires integrated experimental characterization before and after adsorption. BET analysis is widely employed to evaluate variations in surface area and pore volume, while FTIR spectroscopy identifies changes in functional groups and intermolecular interactions. XPS analysis provides information regarding elemental composition, oxidation states, and chemical bonding environments, enabling identification of coordination interactions and electron transfer processes. SEM-EDS analysis reveals morphological and elemental distribution changes, whereas XRD analysis assesses structural stability and crystallinity after adsorption (Zhao et al., 2026). Additional evidence obtained from zeta potential measurements, thermodynamic analysis, kinetic modeling, and adsorption isotherms further clarifies the adsorption mechanism. For example, pseudo-second-order kinetics often indicate chemisorption involving electron sharing or exchange, while Langmuir and Freundlich isotherms help distinguish between monolayer adsorption and heterogeneous surface interactions (Ahmed et al., 2025). Therefore, combining spectroscopic, structural, and adsorption modeling approaches is necessary to accurately identify dominant adsorption pathways and establish structure-performance relationships for advanced MOF-based antibiotic remediation systems.

Table 3 summarizes representative classes of MOFs utilized for the adsorptive removal of antibiotics from aqueous solution, highlighting their surface areas, adsorption capacities, and dominant adsorption mechanisms. The presented studies demonstrate that the adsorption performance of MOFs is strongly influenced by their structural characteristics, including pore architecture, surface functionality, and metal active sites. Zr-based MOFs, such as UiO-series materials, exhibit excellent chemical stability and strong adsorption affinity through hydrogen bonding and electrostatic interactions, whereas Fe-based MOFs provide additional coordination interactions due to the presence of redox-active metal centers. Similarly, ZIF-type materials offer rapid adsorption kinetics and high surface areas, while MOF-based composites further enhance adsorption efficiency through synergistic interfacial interactions and improved structural stability. The reported adsorption capacities indicate the significant potential of MOFs as advanced adsorbents for efficient antibiotic removal from contaminated water.

6 Effect of experimental conditions on adsorption performance

Operational parameters, including pH, temperature, water matrix composition, natural organic matter, heavy metals, and ionic strength, play a critical role in determining the catalytic activity and structural stability of MOFs, as well as the overall efficiency of advanced oxidation processes (Liu B. et al., 2020). The performance of engineered MOFs in antibiotic removal is significantly affected by the complexity of real water matrices (Figure 4), where multiple physicochemical factors interact simultaneously. Variations in pH, dissolved ions, natural organic matter, metal ions, and coexisting organic contaminants can modify adsorption behavior and underlying removal mechanisms. Consequently, these combined effects often reduce removal efficiency relative to controlled laboratory conditions, highlighting the need to evaluate MOF performance under environmentally relevant scenarios. Temperature strongly affects adsorption by influencing molecular diffusion, mass transfer, and adsorbate–adsorbent interactions. Increasing temperature generally enhances adsorption kinetics and helps overcome activation energy barriers; however, it does not always improve adsorption efficiency, particularly in exothermic systems. Therefore, thermodynamic and thermogravimetric analyses are important for understanding temperature-dependent adsorption behavior and material stability (Du et al., 2021). Adsorption capacity exhibits a strong dependence on pH, with optimal performance commonly observed under mildly acidic conditions where multiple interaction mechanisms operate synergistically (Maikano et al., 2026). These observations indicate that pH not only controls adsorption efficiency but also dictates the predominance of specific interaction pathways. The chemical stability of MOFs under extreme pH conditions is governed by the robustness of metal–ligand coordination bonds in acidic and alkaline media. In acidic environments, protonation of coordinating

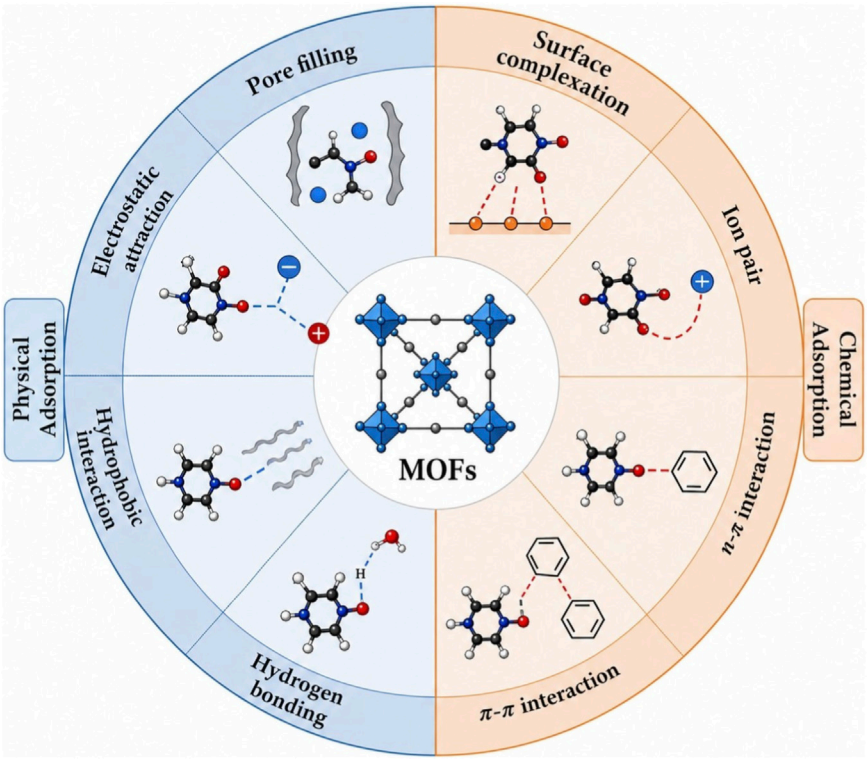


FIGURE 3
Mechanism of antibiotic adsorption by MOFs.

TABLE 3 Different MOFs used for antibiotic adsorption from water.

MOF	Antibiotics	BET surface area (m^2/g)	Capacity (mg/g)	Dominant mechanism	Ref.
MOF-5	Tetracycline	2510	233	H-bonding, π–π, electrostatic	Mirsoleimani-azizi et al. (2018)
MIL-101(Cr)	Pefloxacin	3166	228	Pore filling effect, π-π electrostatic	Nguyen et al. (2024)
Ce-UiO-66	Tetracycline	1131	368.6	π-π, H-bonding, pore filling	Lv et al. (2024)
ZIF-8	Sulfamethoxazole	1890	557	π-π, H-bonding, pore filling	Ahmed et al. (2024)
MOF-808	Chloramphenicol	1431	47	Weak chemical interactions	Mancuso et al. (2026)
Zn/Zr-MOFs	Levofloxacin	96.2	230	Chemisorption	Wei et al. (2024)
UiO-66/MWCNTs	Enrofloxacin	837	134	H-bonding, π–π, electrostatic	Xu et al. (2024)
Cu-MOF@Co-MOF-5	Doxycycline Tetracycline	582	476 435	H-bonding, π–π, electrostatic, pore filling	Yue et al. (2024)
AgN/MOF-5	Metronidazole	983	191	π-π, covalent bonding, H bonding	Oni et al. (2023)
UIO-66@ Cr-MIL-101	Amoxicillin	1025	1111	Chemisorption	Sharafinia et al. (2023)

groups, such as carboxylates, competes with metal coordination, leading to bond cleavage and framework decomposition. In basic conditions, hydroxide ions can attack metal centers or deprotonate coordinated species, resulting in the formation of metal hydroxides or oxides and structural collapse. Stability varies significantly with the metal node; for example, zirconium-based MOFs such as UiO-66 exhibit exceptional stability across a wide pH range (1–11) due to strong Zr-O bonds and high cluster connectivity, whereas zinc-based frameworks like MOF-5 rapidly degrade under mild acidic or basic conditions. Ionic strength significantly influences electrostatic interactions between antibiotic molecules and MOF surfaces. The presence of dissolved salts compresses the electrical double layer, reducing the effective range of electrostatic attraction and thereby decreasing adsorption efficiency (Zheng et al., 2025; Alkhaldi et al., 2026). In addition, competing ions may occupy active sites, particularly in systems dominated by electrostatic mechanisms. As a result, adsorption capacities obtained under low ionic strength laboratory conditions are often overestimated compared to those in real wastewater, where ionic concentrations are substantially higher. Natural organic matter (NOM), commonly present in wastewater, introduces significant complexity to MOF-based antibiotic removal. Components such as humic substances compete directly with antibiotics for active sites, particularly those involving oxygen-containing functional groups, thereby reducing adsorption capacity (Pakzad et al., 2026; Sharma et al., 2026). In addition, NOM can block pore entrances and internal adsorption sites, limit accessibility and decreasing the effective surface area. Surface fouling from NOM adsorption may further alter MOF surface chemistry by masking active sites and modifying surface charge (Sharma et al., 2026). These effects can substantially reduce the removal efficiency of antibiotics such as tetracycline, especially in systems reliant on pore filling and electrostatic interactions (Li and Li, 2026; Mashkoor et al., 2026). Consequently, the design of MOFs with enhanced resistance to fouling and competitive adsorption is essential for effective performance in real wastewater conditions. Metal ions in wastewater can exert both inhibitory and synergistic effects on antibiotic adsorption, depending on system conditions and MOF properties (El-Fawal et al., 2026). Divalent cations such as Cu^{2+}, Zn^{2+}, and Pb^{2+} may compete with antibiotics for active sites, thereby reducing removal efficiency. Conversely, they can enhance adsorption via metal-bridging interactions, forming ternary complexes between the antibiotic, metal ions, and MOF surface, which may stabilize binding or introduce additional coordination pathways (Jin et al., 2026). This dual role highlights the complexity of multicomponent systems, emphasizing that adsorption behavior cannot be reliably predicted from single-solute studies. Accordingly, MOF design should account for both competitive and cooperative interactions in metal-rich environments. The presence of inorganic ions, including Cl^{-}, SO_4^{2-}, PO_4^{3-}, and CO_3^{2-}, significantly influences antibiotic adsorption on MOF surfaces. These ions can compete with antibiotics for active sites or alter solution chemistry in ways that reduce adsorption efficiency. For instance, phosphate and carbonate ions may inhibit adsorption by occupying binding sites or increasing solution pH, thereby shifting antibiotics to less favorable forms. Sulfate ions can also interfere through competitive interactions and by modifying ionic strength (Lin et al., 2026; Iqbal D. et al., 2025). Although certain MOFs exhibit resistance to ionic interference, particularly those with hierarchical porosity or strong binding sites, many systems show diminished performance under high ionic strength conditions. In wastewater systems, antibiotics coexist with a range of organic contaminants, including other pharmaceuticals, dyes, and PFAS. These compounds compete for available adsorption sites on MOFs, reducing selectivity and diminishing the removal efficiency of individual pollutants. These findings underscore the necessity of evaluating adsorption behavior under realistic wastewater conditions.

7 Current challenges and future perspective

A major challenge in the application of MOFs is the discrepancy between laboratory performance and real-world outcomes. Most studies are conducted under simplified conditions, such as single-solute systems, controlled pH, and low ionic strength, which do not adequately represent the complexity of actual wastewater. In real environmental matrices, factors including pH fluctuations, ionic competition, natural organic matter fouling, and multi-contaminant interactions often lead to significantly reduced adsorption efficiency. MOFs are considered efficient, facile, and potentially cost-effective adsorbents for antibiotic removal from water. However, several challenges (Figure 5) must be addressed before their large-scale application in real wastewater treatment systems, including the development of low-cost synthesis routes, structural stability and reusability, scalable production, insufficient selectivity toward target contaminants, cost-effective regeneration methods, and reduced performance under harsh environmental conditions (Maikano et al., 2026). In addition, efficient post-treatment separation remains a critical requirement for practical wastewater treatment applications. To address the limitations of MOFs in practical antibiotic remediation, future research should shift from laboratory-scale batch studies toward integrated, application-oriented engineering strategies. Advanced computational approaches, including density functional theory, molecular simulations, and machine learning, offer promising pathways for the rational design of MOFs with optimized metal nodes, organic linkers, pore structures, and functional groups for selective antibiotic adsorption. These data-driven strategies can accelerate the development of MOFs with improved chemical stability, water resistance, adsorption selectivity, and scalability while reducing synthesis cost and experimental time. Nevertheless, despite substantial laboratory-scale progress, the large-scale implementation of MOF-based water treatment systems remains constrained by operational, economic, and environmental challenges. Practical application of MOFs requires transitioning from batch adsorption to continuous-flow systems such as fixed-bed columns and membrane-assisted reactors (Al-Amran et al., 2025; Zhang et al., 2026). Key challenges include pressure drop, hydraulic stability, particle aggregation, and adsorbent recovery. Immobilization of MOFs into membranes, beads, monoliths, or magnetic composites can improve mechanical stability and facilitate separation; however, it may also reduce surface area and mass transfer efficiency, requiring a balance between stability and adsorption performance. The fixed-bed column process is a conventional water treatment technique in which an adsorbent

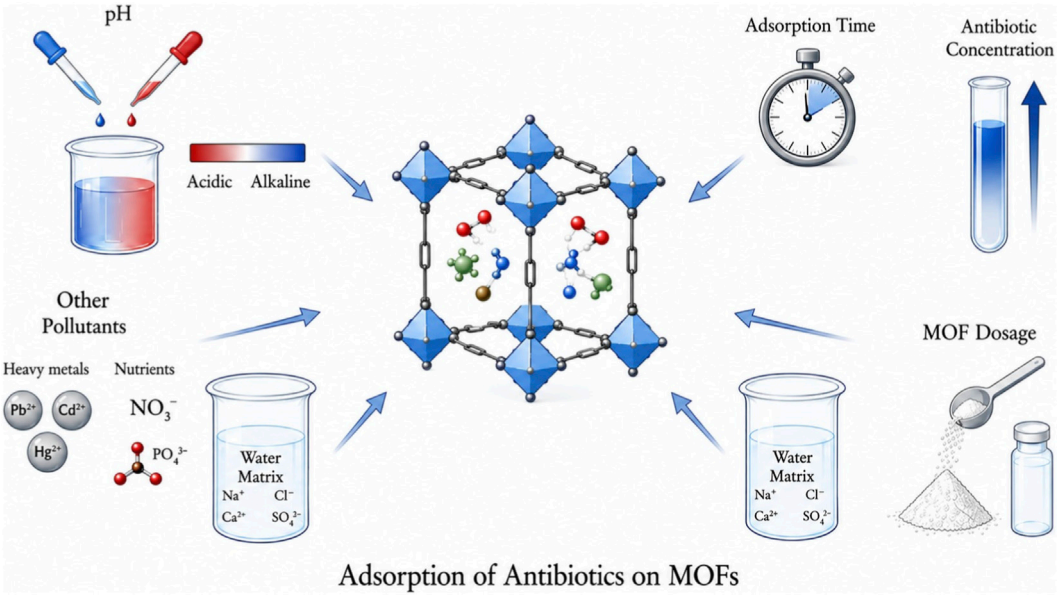


FIGURE 4
Effect of environmental conditions on adsorption performance.

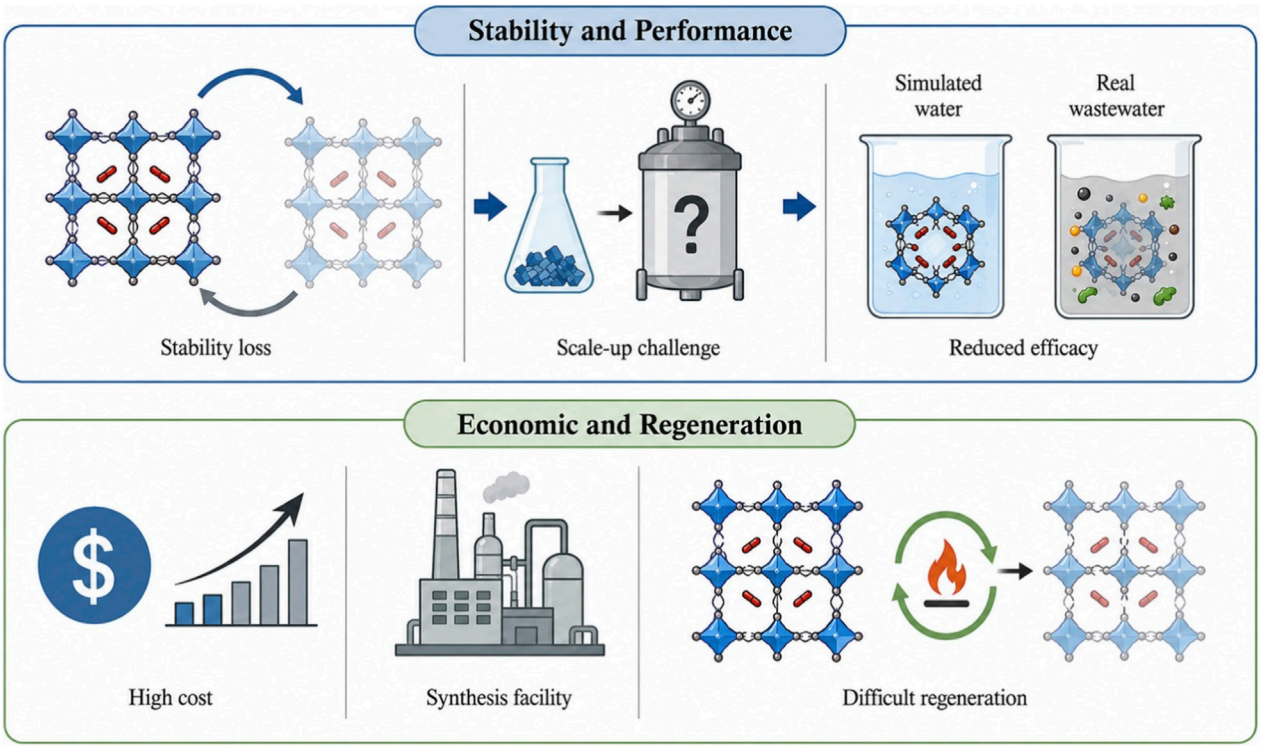


FIGURE 5
Limitations of MOFs for antibiotic removal in real wastewater.

is packed into a column reactor to form a stationary bed. The contaminated fluid continuously flows through the bed under gravity or pressure, allowing pollutants to be removed through the physicochemical interactions of the adsorbent. The incorporation of MOFs as packing materials enhances adsorption performance and enables the efficient removal of antibiotic contaminants from water (Duong et al., 2025). The long-term stability and regeneration of MOFs remain critical challenges for sustainable

application. Repeated adsorption-desorption cycles can cause framework degradation, pore blockage, metal leaching, and loss of active sites, particularly under harsh wastewater conditions (Yuan et al., 2026). While strong thermal or chemical regeneration may restore adsorption capacity, it often accelerates structural deterioration and increases operational cost. In contrast, mild regeneration better preserves framework integrity but may lead to incomplete desorption and gradual performance loss. MOFs with robust metal–ligand bonds and chemically stable functional groups generally exhibit improved cycling stability; however, long-term studies under realistic operating conditions remain limited. A major challenge in MOF-based antibiotic removal is the complexity of real wastewater matrices. Most studies rely on synthetic single-antibiotic solutions under controlled conditions, which poorly represent practical environments. In real wastewater, natural organic matter, inorganic ions, surfactants, and competing contaminants can induce pore blockage, site competition, electrostatic shielding, and fouling, thereby reducing adsorption selectivity and efficiency. Therefore, future research should focus on real wastewater applications and develop antifouling strategies, surface modifications, and hierarchical pore structures to enhance performance under complex conditions. Environmental safety and sustainability are critical for the large-scale application of MOFs. Metal leaching from transition metal-based MOFs may cause secondary pollution and ecotoxicological risks, necessitating comprehensive toxicity assessments of MOF components, degradation products, and spent adsorbents. In addition, the regeneration and disposal of antibiotic-loaded adsorbents must be carefully managed to prevent environmental release. Techno-economic and life-cycle assessments are also essential to evaluate synthesis cost, energy demand, regeneration efficiency, and overall process feasibility. Therefore, future research should emphasize the development of cost-effective, environmentally safe, and operationally stable MOF systems for long-term water treatment applications. Magnetic MOFs offer improved adsorbent recovery and reusability; however, their long-term performance depends on the stability of the magnetic components and resistance to metal leaching. The hard and soft acids and bases theory provides an effective strategy for designing water-stable MOFs through stronger metal-ligand coordination (Shen et al., 2026). Additionally, utilizing waste-derived metal sources and organic ligands offers a sustainable and cost-effective approach for MOF synthesis, enhancing both environmental sustainability and practical applicability in water treatment systems. The transformation of waste into high-value MOFs for antibiotic removal offers a sustainable strategy to simultaneously address waste management and water pollution issues. However, the inherent heterogeneity of waste streams can affect the purity, crystallinity, and structural consistency of the resulting MOFs, potentially limiting their performance and large-scale applicability. Various waste sources, including electronic waste, industrial sludge, and plastic waste (Slater et al., 2019), and biomass residues, can serve as precursors due to their richness in transition metals and organic components. E-wastes, such as printed circuit boards, spent mobile devices, batteries, and photovoltaic panels, contains a valuable secondary resource for metals including Al, Cu, Zn, Ni, Fe, Cr, and Co (Pham et al., 2022). These metals can be recovered through acid leaching using strong acids such as HCl, HNO_3, or H_2SO_4, followed by purification steps. Similarly, industrial by-products such as carbon black and metal-containing sludge from wastewater treatment plants provide alternative metal sources for MOF synthesis (Zhan et al., 2018; Zhao et al., 2023). In parallel, the development of sustainable organic linkers is essential, as conventional ligands are typically derived from petrochemical routes. Waste plastics and agro-industrial biomass offer promising renewable feedstocks for ligand production, supporting greener and more sustainable MOF synthesis strategies. The synthesis of MOFs from waste materials is predominantly achieved through hydrothermal, microwave-assisted, and mechanochemical routes, with the selected method depending on the nature of the metal and ligand precursors (Vellingiri et al., 2018; Keshta et al., 2024). Two main strategies are employed: a multistep approach, involving the conversion of waste into purified metal ions or organic linkers prior to MOF synthesis, and a one-pot approach, where waste transformation and framework formation occur simultaneously under compatible conditions. Waste-derived MOFs have emerged as sustainable and cost-effective adsorbents with physicochemical properties and adsorption efficiencies comparable to those of MOFs synthesized from commercial precursors (Heng et al., 2023). Recent studies demonstrated that these materials possess high adsorption capacities, excellent structural stability, and favorable regeneration performance for antibiotic removal from aqueous environments (Shazadi et al., 2026). For a more economically feasible and sustainable process, the utilization of waste plastic materials as alternative organic linker sources for MOF synthesis has attracted increasing attention, offering an environmentally friendly strategy for large-scale production. Greater sustainability can also be achieved when both metal precursors and organic linkers are derived from waste resources in the presence of green solvents obtained from waste materials (El-Sayed and Yuan, 2020; Chaudhary et al., 2025). Such integrated approaches not only reduce synthesis costs and environmental impacts but also promote waste valorization and circular economy principles for advanced wastewater treatment applications. Current research trends highlight the transformation of MOFs from conventional adsorbents into multifunctional platforms capable of integrating adsorption and degradation processes (Alamdari and Journey, 2026). In particular, the coupling of MOFs with advanced oxidation processes (AOPs), including photocatalysis, Fenton-like reactions, and ozonation systems, has attracted considerable attention due to its potential to achieve enhanced antibiotic removal efficiency, rapid degradation kinetics, and improved mineralization of persistent contaminants (Aziz et al., 2025b). For example, Zr-based MOFs (e.g., UiO-66) and porphyrin-based frameworks are being engineered to combine high adsorption capacity within situ photocatalytic degradation (Zong et al., 2021). This integrated strategy not only removes antibiotics from aqueous media but also minimizes the risk of secondary pollution by facilitating their mineralization into CO_2, water, and benign inorganic products directly on the MOF surface.

8 Conclusion and outlook

The occurrence of antibiotics in aquatic environments has increased markedly due to continuous inputs from pharmaceutical

manufacturing, industrial discharges, and healthcare-related sources. This persistent contamination, largely exacerbated by the insufficient efficiency of conventional wastewater treatment technologies, poses a serious global environmental and public health concern, particularly in relation to the spread of antimicrobial resistance. Accordingly, the development of efficient, sustainable, and scalable treatment strategies is urgently required. Among emerging materials, engineered MOFs have demonstrated exceptional promise for antibiotic removal owing to their structural tunability, high surface area, and diverse adsorption and catalytic functionalities. The literature indicates that their performance is strongly influenced by precursor selection, metal node type, synthesis conditions, and post-synthetic modification, with adsorption processes mainly driven by pore filling, π–π interactions, hydrogen bonding, electrostatic attraction, and surface complexation. Despite these advantages, significant challenges remain in translating laboratory-scale achievements into real-world applications. The complexity of actual water matrices, including competing ions, natural organic matter, and coexisting contaminants, can substantially hinder performance. Moreover, issues related to regeneration efficiency, long-term stability, scalable synthesis, and economic feasibility must be addressed. Future research should prioritize the design of robust and application-oriented MOFs through realistic environmental assessments, process optimization, and sustainable material engineering. In particular, the integration of computational chemistry and machine learning offers a promising pathway for the rational design and screening of MOFs with tailored active sites and enhanced stability. Such strategies are expected to accelerate the development of cost-effective, scalable, and high-performance MOF-based systems for advanced water purification applications.

Author contributions

KH: Conceptualization, Data curation, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Acknowledgements

I would like to acknowledge the support provided by the University of Sulaimani.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Generative AI was used solely for language editing.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abazari, R., Mahjoub, A. R., and Shariati, J. (2019). Synthesis of a nanostructured pillar MOF with high adsorption capacity towards antibiotics pollutants from aqueous solution. *J. Hazard Mater* 366, 439–451. doi:10.1016/j.jhazmat.2018.12.030

Abbasnia, A., Zarei, A., Yeganeh, M., Sobhi, H. R., Gholami, M., and Esrafili, A. (2022). Removal of tetracycline antibiotics by adsorption and photocatalytic-degradation processes in aqueous solutions using metal organic frameworks (MOFs): a systematic review. *Inorg. Chem. Commun.* 145, 109959. doi:10.1016/j.inoche.2022.109959

Ahmed, M. B., Zhou, J. L., Ngo, H. H., and Guo, W. (2015). Adsorptive removal of antibiotics from water and wastewater: progress and challenges. *Sci. Total Environ.* 532, 112–126. doi:10.1016/j.scitotenv.2015.05.130

Ahmed, I., Yoon, M., and Jhung, S. H. (2024). ZIF-8 templated mesoporous triazine covalent-organic polymer for adsorptive removal of sulfonamides from water. *Chem. Eng. J.* 484, 149578. doi:10.1016/j.cej.2024.149578

Ahmed, H. R., Kayani, K. F., Ealias, A. M., and Aziz, K. H. H. (2025). A comprehensive review of forty adsorption isotherm models: an In-depth analysis of ten statistical error measures. *Water Air Soil Pollut.* 236, 346. doi:10.1007/s11270-025-07982-4

Ahmed, S., Altaf, F., Mir, I., Khan, S. A., Rasheed, L., Shamshad, J., et al. (2026). From synthesis to application: exploring the structure, stability, and functional performance of metal–organic frameworks. *J. Mol. Struct.* 1360, 145437. doi:10.1016/j.molstruc.2026.145437

Al-Amrani, W. A., Mohammed, A. A., and Hanafiah, MAKM (2025). Breaking the batch barrier: magnetic silica gel fixed-bed columns for sustainable acid Orange 10 removal-optimization, regeneration, and cost analysis. *Next Res.* 2, 100652. doi:10.1016/j.nexres.2025.100652

Al-Ghouti, M. A., and Da'ana, D. A. (2020). Guidelines for the use and interpretation of adsorption isotherm models: a review. *J. Hazard Mater* 393, 122383. doi:10.1016/j.jhazmat.2020.122383

Alamdari, A., and Journey, Z. A. (2026). MOF-Based strategies for bisphenol A remediation in water: from adsorption to photocatalytic degradation. *J. Hazard. Mater. Adv.* 22, 101211. doi:10.1016/j.hazadv.2026.101211

Alkhaldi, H. S., Baata, M., Alhajri, F., Elbasiony, A. M., Almoiqli, M. S., Madani, M., et al. (2026). Recent progress in the preparation and environmental applications of functionalized adsorbent hydrogel: a review. *RSC Adv.* 16, 7287–7336. doi:10.1039/D5RA07905E

Alshammari, B. H., Alanazi, K. D., Ahmad, O. A. S., Sallam, S., Al-Bagawi, A. H., Alsehli, A. H., et al. (2024). Tailoring magnetic Sn-MOFs for efficient amoxicillin antibiotic removal through process optimization. *RSC Adv.* 14, 5875–5892. doi:10.1039/D3RA08676C

Ameen, S. S. M., Algethami, F. K., Usman, A. M. L., and Omer, K. M. (2026). Simultaneous detection and removal of tetracycline antibiotics using multifunctional MOFs. *TrAC Trends Anal. Chem.* 199, 118790. doi:10.1016/j.trac.2026.118790

Anjali, R., and Shanthakumar, S. (2019). Insights on the current status of occurrence and removal of antibiotics in wastewater by advanced oxidation processes. *J. Environ. Manage* 246, 51–62. doi:10.1016/j.jenvman.2019.05.090

Aziz, K. H. H., Mustafa, F. S., Hamarawf, R. F., and Omer, K. M. (2025a). Adsorptive removal of toxic heavy metals from aquatic environment by metal organic framework (MOF): a review. *J. Water Process Eng.* 70, 106867. doi:10.1016/j.jwpe.2024.106867

Aziz, K. H. H., Mustafa, F. S., and Hama, S. (2025b). Pharmaceutical removal from aquatic environments using multifunctional metal-organic frameworks (MOFs) materials for adsorption and degradation processes: a review. *Coord. Chem. Rev.* 542, 216875. doi:10.1016/j.ccr.2025.216875

Bai, Y., Li, S., and Ho, S.-H. (2026). How do nanomaterials influence the spread of antibiotic resistance genes in aquatic environments? *Chin. Chem. Lett.* 37, 111183. doi:10.1016/j.cclet.2025.111183

Batool, S. M., Batool, S. S., Aliashghar, B., Thomsan, D., Miranda, M., Braaten, B. D., et al. (2026). Structural modifications in metal–organic frameworks for CO2 adsorption and sensing through sustainable synthesis and emerging designs. *Mater. Today Sustain.* 34, 101321. doi:10.1016/j.mtsust.2026.101321

Ben Hamadi, N., Guesmi, A., Abd El-Fattah, W., Alshammari, B. H., Aldawsari, N. A., El-Desouky, M. G., et al. (2026). Eco-engineered bio-based palladium MOF–chitosan–carboxymethyl cellulose composite sponge: mechanistic insights, box–behnken optimization, and high-performance reusability for advanced ciprofloxacin removal from wastewater. *RSC Adv.* 16, 5013–5039. doi:10.1039/D5RA08409A

Bilal, M., Mehmood, S., Rasheed, T., and Iqbal, H. M. N. (2020). Antibiotics traces in the aquatic environment: persistence and adverse environmental impact. *Curr. Opin. Environ. Sci. Health* 13, 68–74. doi:10.1016/j.coesh.2019.11.005

Bosch, M., Zhang, M., and Zhou, H.-C. (2014). Increasing the stability of metal-organic frameworks. *Adv. Chem.* 2014, 1–8. doi:10.1155/2014/182327

Browne, S., Bhatia, S., Sarkar, N., and Kaushik, M. (2023). "Antibiotic-resistant bacteria and antibiotic-resistant genes in agriculture: a rising alarm for future," in *Degradation of Antibiotics and Antibiotic-Resistant Bacteria from Various Sources*. Elsevier, 247–274. doi:10.1016/B978-0-323-99866-6.00017-9

Buakaew, T., and Ratanatamskul, C. (2026). A review of *in-situ* technologies for enhancement of the removal of pharmaceuticals and personal care products (PPCPs) and mitigation of membrane fouling in membrane bioreactors. *J. Hazard. Mater. Adv.* 21, 100976. doi:10.1016/j.hazadv.2025.100976

Chakhtouna, H., Benzeid, H., Zari, N., Qaiss, A. E. K., and Bouhfid, R. (2023). Microwave-assisted synthesis of MIL–53(Fe)/biochar composite from date palm for ciprofloxacin and ofloxacin antibiotics removal. *Sep. Purif. Technol.* 308, 122850. doi:10.1016/j.seppur.2022.122850

Chandel, A., Kaur, H., Sharma, A., and Kumar, V. (2026). Organic micropollutants in the environment: a literature review. *J. Geochem Explor* 284, 107997. doi:10.1016/j.gexplo.2026.107997

Chaturvedi, G., Kaur, A., Umar, A., Khan, M. A., Algarni, H., and Kansal, S. K. (2020). Removal of fluoroquinolone drug, levofloxacin, from aqueous phase over iron based MOFs, MIL-100(Fe). *J. Solid State Chem.* 281, 121029. doi:10.1016/j.jssc.2019.121029

Chaudhary, R., Kumar, S., and Sharma, V. (2025). Agricultural biowaste valorization towards circular economy: nanoparticles synthesis and biopolymers extraction for wastewater remediation. *Bioresour. Technol. Rep.* 32, 102357. doi:10.1016/j.biteb.2025.102357

Chen, T., Kang, Y., Li, X., and Jiao, H. (2026). Environmental factors regulate the evolution of antibiotic resistance: focusing on fitness costs and compensatory evolution. *J. Environ. Chem. Eng.* 14, 122445. doi:10.1016/j.jece.2026.122445

Deng, W., Jin, M., Fan, C., and Zhang, R. (2025). Deep eutectic solvents for the analysis of antibiotics in foods: recent advances, green perspectives and future directions. *Food Chem.* 494, 146150. doi:10.1016/j.foodchem.2025.146150

Dong, Y., Hu, T., Pudukudy, M., Su, H., Jiang, L., Shan, S., et al. (2020). Influence of microwave-assisted synthesis on the structural and textural properties of mesoporous MIL-101(Fe) and NH2-MIL-101(Fe) for enhanced tetracycline adsorption. *Mater Chem. Phys.* 251, 123060. doi:10.1016/j.matchemphys.2020.123060

Du, C., Zhang, Z., Yu, G., Wu, H., Chen, H., Zhou, L., et al. (2021). A review of metal organic framework (MOFs)-based materials for antibiotics removal via adsorption and photocatalysis. *Chemosphere* 272, 129501. doi:10.1016/j.chemosphere.2020.129501

Duo, H., Yue, J., Wan, X., Sha, L., Hou, X., and Zhu, Q. (2023). Recent advances in synthesis and applications of metal–organic frameworks for sample preparation in antibiotic analysis. *Microchem. J.* 193, 109053. doi:10.1016/j.microc.2023.109053

Duong, Q. P., Le, T. P., Vo, T. M. T., Dang, H. G., Cao, N. H. L., Ngo, T. N. M., et al. (2025). Removal of ciprofloxacin from water using pH-tunable GO/chitosan beads: batch and fixed-bed column studies with breakthrough modeling and regeneration. *J. Water Process Eng.* 79, 108915. doi:10.1016/j.jwpe.2025.108915

El-Fawal, E. M., El Naggar, A. M. A., and Zaki, T. (2026). Dual-metal/binary-linker MOF with DABCO pillaring for high-performance visible-light photocatalytic degradation of organic contaminants in model and real industrial wastewater. *J. Environ. Manage* 401, 128948. doi:10.1016/j.jenvman.2026.128948

El-Sawaf, A. K., Nassar, A. A., Mubarak, M. F., and Hemdan, M. (2026). Nanoarchitectonics of metal–organic framework technologies for dual antibiotic adsorption and photocatalytic degradation in water treatment. *J. Inorg. Organomet. Polym. Mater*. doi:10.1007/s10904-026-04196-x

El-Sayed, E.-S. M., and Yuan, D. (2020). Waste to MOFs: sustainable linker, metal, and solvent sources for value-added MOF synthesis and applications. *Green Chem.* 22, 4082–4104. doi:10.1039/D0GC00353K

Fakorede, E. O., Ajibade, F. O., Adewumi, J. R., and Ighalo, J. O. (2026). Antibiotic contamination in Nigeria: occurrence, impacts, and sustainable wastewater management solutions. *Reg. Stud. Mar. Sci.* 95, 104842. doi:10.1016/j.rsma.2026.104842

Fang, Z., Bueken, B., De Vos, D. E., and Fischer, R. A. (2015). Defect-engineered metal–organic frameworks. *Angew. Chem. Int. Ed.* 54, 7234–7254. doi:10.1002/anie.201411540

Gao, Y., Wang, F., Wang, C.-C., and Yi, X.-H. (2024). Microwave-assisted production of metal-organic frameworks for water purification: a mini-review. *Surfaces Interfaces* 44, 103724. doi:10.1016/j.surfin.2023.103724

Gul, S., Xueqian, G., Gomaa, H., Tariq, M. A., Kong, D.-M., and Zhu, L.-N. (2026). Efficient removal of tetracycline by a hydrogel/MOF composite: combined experimental and DFT study. *Sep. Purif. Technol.* 398, 138261. doi:10.1016/j.seppur.2026.138261

Ha, H. Q., Nguyen, NPT, Nguyen, T. T. T., and Tran, T. V. (2026). Removal of selected antibiotics and anti-inflammatory drugs using metal–organic framework-based adsorbents. *J. Industrial Eng. Chem.* 156, 60–77. doi:10.1016/j.jiec.2025.08.049

Hama Aziz, K. H., Mustafa, F. S., Karim, M. A. H., and Hama, S. (2025). Pharmaceutical pollution in the aquatic environment: advanced oxidation processes as efficient treatment approaches: a review. *Mater Adv.* 6, 3433–3454. doi:10.1039/D4MA01122H

Hama, A. K. H., Mustafa, F. S., Karim, M. A. H., and Hama, S. (2025). Biochar-based catalysts: an efficient and sustainable approach for water remediation from organic pollutants via advanced oxidation processes. *J. Environ. Manage* 390, 126245. doi:10.1016/j.jenvman.2025.126245

Han, Y., Yang, L., Chen, X., Cai, Y., Zhang, X., Qian, M., et al. (2020). Removal of veterinary antibiotics from swine wastewater using anaerobic and aerobic biodegradation. *Sci. Total Environ.* 709, 136094. doi:10.1016/j.scitotenv.2019.136094

Han, Z., Yang, Y., Rushlow, J., Huo, J., Liu, Z., Hsu, Y.-C., et al. (2025). Development of the design and synthesis of metal–organic frameworks (MOFs) – from large scale attempts, functional oriented modifications, to artificial intelligence (AI) predictions. *Chem. Soc. Rev.* 54, 367–395. doi:10.1039/D4CS00432A

Hemavathy, R. V., Kamalesh, R., Thamarai, P., Saravanan, A., Yaashikaa, P. R., Vickram, A. S., et al. (2026). Advances in adsorptive clean water remediation using covalent organic frameworks: synthesis, application, and lifecycle insights. *Phys. Chem. Earth, Parts A/B/C* 143, 104339. doi:10.1016/j.pce.2026.104339

Heng, Y., Fang, Z., Li, J., Luo, L., Zheng, M., and Huang, H. (2023). Defective metal–organic framework derived from the waste plastic bottles for rapid and efficient nitroimidazole antibiotics removal. *J. Colloid Interface Sci.* 650, 836–845. doi:10.1016/j.jcis.2023.07.049

Hu, H., and Huang, J. (2026). Reticular-to-reactor carbon platforms: MOF/COF-derived hierarchically porous carbons for selective capture-and-kill water remediation. *Surfaces Interfaces* 91, 109327. doi:10.1016/j.surfin.2026.109327

Hu, H., Liu, J., Zheng, X., Zhao, K., Lin, Y., Xu, X., et al. (2025). Recent advances in iron-based catalyst-driven persulfate activation for organic pollutant degradation. *J. Water Process Eng.* 71, 107423. doi:10.1016/j.jwpe.2025.107423

Iqbal, A., Ullah, H., Iqbal, M., Khan, M. S., Ullah, R. S., Gul, Z., et al. (2025a). MOF UiO-66 and its composites: design strategies and applications in drug and antibiotic removal. *Environ. Sci. Pollut. Res.* 33, 5767–5794. doi:10.1007/s11356-025-35922-6

Iqbal, D., Sarwar, M. I., Wu, Q., Hussain, A., Peng, F., and Yue, W. (2025b). Dual-functional cellulose-MOF hybrid membranes: synergistic removal and disinfection for tackling antibiotic pollution. *Chem. Eng. J.* 524, 169644. doi:10.1016/j.cej.2025.169644

Jin, L., Li, C., Addou, A. M., Zhang, S., and Li, H. (2026). Global heavy metal-antibiotic co-pollution: distribution, ARG co-selection, toxic synergism, and AOPs-mediated remediation with focus on non-radical pathways. *J. Hazard Mater* 506, 141601. doi:10.1016/j.jhazmat.2026.141601

Kamalesh, R., and Saravanan, A. (2026). Sustainable ANN-Driven modelling and characterisation of Rhodamine-B removal using ZIF-8 functionalised pomegranate peel waste adsorbent supporting clean water and sanitation initiatives. *Hybrid. Adv.* 12, 100625. doi:10.1016/j.hybadv.2026.100625

Kamalesh, R., Shaji, A., Saravanan, A., Y, P. R., and Vickram, A. S. (2026). Metal–organic frameworks for heavy metal remediation: advances in sustainable adsorption mechanisms and clean water applications. *Hybrid. Adv.* 12, 100608. doi:10.1016/j.hybadv.2026.100608

Karki, B. K., Shrestha, S., Poudel, S., Angove, M. J., Gupta, R. K., and Paudel, S. R. (2026). Potential antibiotics contamination in aquaponic systems: antimicrobial gene, mitigation and treatment approaches. *Aquac. Fish.* 11, 463–479. doi:10.1016/j.aaf.2025.11.006

Karthik, V., Thirunavukkarasu, A., Nithya, R., Janani, P., Evelin, J. A., Bhuvaneshwari, S., et al. (2025). Adsorptive removal of antibiotics from wastewater: a critical review of challenges and research gaps. *Sustain. Chem. One World* 8, 100107. doi:10.1016/j.scowo.2025.100107

Kawsar, M. A., Shahriar, F., Adikari, D., Hasan, M. T., and Zhang, Y. (2026). Exploring antibiotics and antimicrobial resistance (AMR) in aquaculture: what have we learned from Bangladesh? *Water Biol. Secur.*, 100586. doi:10.1016/j.watbs.2026.100586

Keshta, B. E., Yu, H., Wang, L., and Gemeay, A. H. (2024). Cutting-edge in the green synthesis of MIL-101(Cr) MOF based on organic and inorganic waste recycling with extraordinary removal for anionic dye. *Sep. Purif. Technol.* 332, 125744. doi:10.1016/j.seppur.2023.125744

Kukkar, P., and Kukkar, D. (2025). Recent breakthroughs in the solvothermal assisted synthesis of luminescent metal-organic frameworks. *Inorg. Chem. Commun.* 178, 114631. doi:10.1016/j.inoche.2025.114631

Li, X., and Li, Z. (2026). Application and development of biochar adsorbents for emerging contaminants removal from wastewater: critical synthesis and scientometric perspective. *J. Environ. Chem. Eng.* 14, 121189. doi:10.1016/j.jece.2026.121189

Li, J., Lin, G., Liang, H., Wang, S., Hu, T., Li, S., et al. (2025a). Recent advances in the synthesis of MOF-Based composites for heavy-metal ion adsorption. *Coord. Chem. Rev.* 545, 217010. doi:10.1016/j.ccr.2025.217010

Li, J., Wang, H., Wang, X., Ye, J., Wang, X., and Xue, B. (2025b). Nickel-doped Zn-MOF for efficient adsorption of norfloxacin antibiotic: adsorption behaviors and mechanisms. *Mater Chem. Phys.* 343, 131005. doi:10.1016/j.matchemphys.2025.131005

Lin, X., Chen, Y., Li, K., Han, X., Zhang, X., Li, Y., et al. (2026). A floatable and anisotropic composite aerogel for enhanced synergistic adsorption-catalysis of antibiotics in marine aquaculture wastewater. *Desalination* 618, 119504. doi:10.1016/j.desal.2025.119504

Liu, X., Huang, D., Lai, C., Zeng, G., Qin, L., Wang, H., et al. (2019). Recent advances in covalent organic frameworks (COFs) as a smart sensing material. *Chem. Soc. Rev.* 48, 5266–5302. doi:10.1039/C9CS00299E

Liu, L., Cui, W., Lu, C., Zain, A., Zhang, W., Shen, G., et al. (2020a). Analyzing the adsorptive behavior of amoxicillin on four Zr-MOFs nanoparticles: functional groups dependence of adsorption performance and mechanisms. *J. Environ. Manage* 268, 110630. doi:10.1016/j.jenvman.2020.110630

Liu, B., Vikrant, K., Kim, K.-H., Kumar, V., and Kailasa, S. K. (2020b). Critical role of water stability in metal–organic frameworks and advanced modification strategies for the extension of their applicability. *Environ. Sci. Nano* 7, 1319–1347. doi:10.1039/C9EN01321K

Liu, H., Zhang, H., Dong, X., Wu, C., and Lichtfouse, E. (2023a). Removal of antibiotics from Black water by a membrane filtration-visible light photocatalytic system. *J. Water Process Eng.* 53, 103605. doi:10.1016/j.jwpe.2023.103605

Liu, H.-X., Cui, Y.-Y., Abdukayum, A., and Yang, C.-X. (2023b). Ultrafast ultrasound-assisted synthesis of microporous organic networks for the efficient removal of antibiotics. *New J. Chem.* 47, 19578–19587. doi:10.1039/D3NJ03509C

Lv, Q., Bi, L., Shi, L., Yang, L., Liu, P., Li, X., et al. (2024). Simultaneous removal of antibiotics and metal oxoanions from aqueous solution by Ce-doped UiO-66: removal mechanisms and solid phase extraction. *Sep. Purif. Technol.* 330, 125451. doi:10.1016/j.seppur.2023.125451

Ma, B., Qin, N., Yan, Q., Zhou, W., Zhang, S., Wang, X., et al. (2026). Advancing metal organic framework and covalent organic framework design *via* the digital-intelligent paradigm. *Digit. Discov.* 5, 523–547. doi:10.1039/D5DD00401B

Mahmoud, M. E., Amira, M. F., Seleim, S. M., and Mohamed, A. K. (2020). Metal–organic framework-functionalized copper–amine complex: a robust nanocomposite for doxycycline antibiotic removal. *J. Chem. Eng. Data* 65, 3546–3559. doi:10.1021/acs.jced.0c00112

Mahmoud, E. K., Mahmoud, H. M., and Taha, M. (2024). Utilizing metal-organic framework porosity for efficient antibiotic separation and sustained release. *Surfaces Interfaces* 55, 105385. doi:10.1016/j.surfin.2024.105385

Maikano, H., Yahya, M. D., Baba, I. A., Abdulkareem, A. S., Tijani, J. O., Olutoye, M. A., et al. (2026). Advances in nanomaterials for efficient petrochemical wastewater treatment: synergistic removal of organic and inorganic pollutants. *Chem. Eng. J. Adv.* 26, 101144. doi:10.1016/j.ceja.2026.101144

Maleki, B., Esmaeili, H., Venkatesh, Y. K., and Yusuf, M. (2024). A critical review on MOFs and COFs-based heterogeneous catalysts in biodiesel generation: synthesis methods, structural features, mechanisms, kinetic, economic/environmental evaluation, and their performance. *Process Saf. Environ. Prot.* 187, 903–925. doi:10.1016/j.psep.2024.04.144

Mancuso, A., Vigara, A. A., Pipolo, A., Sacco, O., Cabello, C. P., Palomino, G. T., et al. (2026). Facile fabrication of a reusable MOF-808@3D-printed device for the efficient adsorptive removal of chloramphenicol from water. *J. Water Process Eng.* 83, 109715. doi:10.1016/j.jwpe.2026.109715

Mangla, D., Annu, S. A., and Ikram, S. (2022). Critical review on adsorptive removal of antibiotics: present situation, challenges and future perspective. *J. Hazard Mater* 425, 127946. doi:10.1016/j.jhazmat.2021.127946

Marrett, J. M., Effaty, F., Ottenwaelder, X., and Friščić, T. (2025). Mechanochemistry for metal–organic frameworks and covalent–organic frameworks (MOFs, COFs): methods, materials, and mechanisms. *Adv. Mater.* 37, 2418707. doi:10.1002/adma.202418707

Mashkoor, F., Shoeb, M., Mashkoor, R., Kalam, A., and Jeong, C. (2026). Coordination-engineered MOFs for PFAS "forever chemicals" remediation: from molecular recognition to capture-to-destruction architectures. *Coord. Chem. Rev.* 559, 217818. doi:10.1016/j.ccr.2026.217818

Mei, R.-X., Wang, P., Yi, X.-H., and Wang, C.-C. (2025). Engineering MOF-Based homojunction photocatalysts for sustainable energy and environment. *Environ. Sci. Nano* 12, 5102–5115. doi:10.1039/D5EN00657K

Mirizadeh, S., Casazza, A. A., and Converti, A. (2026). Exploring the synergistic sorption capacities of magnetic-chitosan-arthrospira platensis biocomposite for simultaneous removal of tetracycline and heavy metals. *J. Hazard. Mater. Organics* 3, 100026. doi:10.1016/j.hazmo.2026.100026

Mirsoleimani-azizi, S. M., Setoodeh, P., Zeinali, S., and Rahimpour, M. R. (2018). Tetracycline antibiotic removal from aqueous solutions by MOF-5: adsorption isotherm, kinetic and thermodynamic studies. *J. Environ. Chem. Eng.* 6, 6118–6130. doi:10.1016/j.jece.2018.09.017

Mubarak, N. M. (2026). Holistic insight mechanism of MOF-Based materials for wastewater treatment. *J. Environ. Chem. Eng.* 14, 122307. doi:10.1016/j.jece.2026.122307

Nasar, A. (2026). Carbon-based adsorbents for removing pharmaceuticals from wastewater: a critical review. *JCIS Open* 22, 100175. doi:10.1016/j.jciso.2026.100175

Nassri, I., khattabi rifi, S., Sayerh, F., and Souabi, S. (2023). Occurrence, pollution sources, and mitigation prospects of antibiotics, anti-inflammatories, and endocrine disruptors in the aquatic environment. *Environ. Nanotechnol. Monit. Manag.* 20, 100878. doi:10.1016/j.enmm.2023.100878

Nguyen, T. T., Nguyen, M. K., Kumar, V., Huu Do, H., Thi Kim Le, A., Van Nguyen, A., et al. (2024). Optimal adsorption of pefloxacin antibiotics from aqueous solutions: improved performance with metal-organic framework MIL-101(Cr). *Colloids Surf. A Physicochem Eng. Asp.* 689, 133642. doi:10.1016/j.colsurfa.2024.133642

Okeke, E. S., Chukwudozie, K. I., Nyaruaba, R., Ita, R. E., Oladipo, A., Ejeromedoghene, O., et al. (2022). Antibiotic resistance in aquaculture and aquatic organisms: a review of current nanotechnology applications for sustainable management. *Environ. Sci. Pollut. Res.* 29, 69241–69274. doi:10.1007/s11356-022-22319-y

Okeke, E. S., Nwankwo, C. E. I., Ezeorba, T. P. C., Ogugofor, M. O., and Nwuche, C. O. (2025). Antibiotic residues and antibiotic resistance genes in African water systems: implications for safe drinking water, aquatic ecosystems, and sustainable development goals. *J. Water Process Eng.* 69, 106636. doi:10.1016/j.jwpe.2024.106636

Oni, B. A., Sanni, S. E., Agu, K. C., and Tomomewo, O. S. (2023). Green synthesis of Ag nanoparticles from Argemone mexicana L. leaf extract coated with MOF-5 for the removal of metronidazole antibiotics from aqueous solution. *J. Environ. Manage* 342, 118161. doi:10.1016/j.jenvman.2023.118161

Pakzad, K., Antonietti, M., and Volikov, A. (2026). Environmental remediation of antibiotics and herbicides using artificial humic substances. *Sep. Purif. Technol.* 394, 137508. doi:10.1016/j.seppur.2026.137508

Park, C., Song, J., Lee, G., and Hong, H.-J. (2025). Mechanistic study of direct Mg-Al layered double hydroxide formation for the removal of amphoteric ciprofloxacin(CIP) antibiotics from aqueous media. *Sep. Purif. Technol.* 367, 132901. doi:10.1016/j.seppur.2025.132901

Pham, H. K., Sim, Y., Carboni, M., Meyer, D., and Mathews, N. (2022). Generating metal-organic frameworks (MOFs) from photovoltaic modules for wastewater remediation. *J. Environ. Chem. Eng.* 10, 108346. doi:10.1016/j.jece.2022.108346

Poomipuen, K., Chokejaroenrat, C., Jermnak, U., Angkaew, A., Chopjitt, P., Satchasataporn, K., et al. (2026). Development of yttrium-copper oxide on mxene surface for boron doped diamond electrodes of electrochemical treatment for antibiotic removal. *Desalination* 628, 120059. doi:10.1016/j.desal.2026.120059

Pooresmaeil, M., and Namazi, H. (2026). Fabrication of bio-based magnetic and porous MOF(Ce)@Alg/MG for the efficient antibiotic removal from aqueous solution. *Colloids Surf. A Physicochem Eng. Asp.* 739, 140120. doi:10.1016/j.colsurfa.2026.140120

Qian, J., Cheng, Z., Wang, J., Zhang, Y., Zeng, L., and Chang, H. (2026). Recycling algal blooms into biochar for antibiotics removal and scale-up adaption. *J. Water Process Eng.* 87, 110135. doi:10.1016/j.jwpe.2026.110135

Qin, M., Shi, Y., Lu, D., Deng, J., Shi, G., and Zhou, T. (2022). High-performance Hf/Ti-Doped defective Zr-MOFs for cefoperazone adsorption: behavior and mechanisms. *Appl. Surf. Sci.* 595, 153494. doi:10.1016/j.apsusc.2022.153494

Ren, Q., Hu, L., Wei, F., Shang, W., Li, M., and Liang, Z. (2026). Preparation of Zn/Mn-MOFs/GO composites and adsorption of minocycline and Orange IV in aqueous solution. *Mater Today Commun.* 52, 114991. doi:10.1016/j.mtcomm.2026.114991

Rr, R., and Haimbodi, R. (2026). Recent advances in ZnO/MOFs: synthesis, characterization, and applications in sustainable antibiotic wastewater treatment. *Chin. J. Anal. Chem.* 54, 100619. doi:10.1016/j.cjac.2025.100619

Saravanan, A., Swaminaathan, P., Kumar, P. S., Yaashikaa, P. R., Kamalesh, R., and Rangasamy, G. (2023). A comprehensive review on immobilized microbes - biochar and their environmental remediation: mechanism, challenges and future perspectives. *Environ. Res.* 236, 116723. doi:10.1016/j.envres.2023.116723

Sardar, M., Omer, K. M., Mohammad Ameen, S. S., and Hama, A. K. H. (2026). Fluorescence-based detection of antibiotics in aquatic environments using carbon nanodots: a review. *RSC Sustain.* 4, 1230–1251. doi:10.1039/D5SU00816F

Senthil Raja, D., and Tsai, D.-H. (2024). Recent advances in continuous flow synthesis of metal–organic frameworks and their composites. *Chem. Commun.* 60, 8497–8515. doi:10.1039/D4CC02088J

Shah, S. S. A., Khan, N. A., Rehman, A. U., Murtaza, G., Ashiq, S., Nazir, M. A., et al. (2024). Removal of antibiotics from wastewater via metal-organic frameworks (MOFs) as adsorbents. *Toxin Rev.* 43, 277–299. doi:10.1080/15569543.2024.2329921

Sharafinia, S., Rashidi, A., Tabarkhoon, F., Dehghan, F., Tabarkhoon, F., and Bazmi, M. (2023). Effective adsorption of amoxicillin by using UIO-66@ Cr-MIL-101 nanohybrid: isotherm, kinetic, thermodynamic, and optimization by central composite design. *Sci. Rep.* 13, 22689. doi:10.1038/s41598-023-49393-7

Sharma, G., Verma, A., Zhi, J., Wang, T., Verma, Y., Dhiman, P., et al. (2026). Heteroatom-doped MOFs as hybrid materials for the removal of organic pollutants. *Coord. Chem. Rev.* 549, 217260. doi:10.1016/j.ccr.2025.217260

Shazadi, B., Bazmi, A. A., Yasin, M., Gilani, M. A., and Khan, A. L. (2026). Upcycling waste polyethylene terephthalate (PET) bottles into high-performance aluminum based metal organic frameworks (MOFs) for sustainable antibiotic removal from water. *Results Eng.* 29, 108619. doi:10.1016/j.rineng.2025.108619

Shen, Y., Kang, J., Guo, L., Qiu, F., Fan, Y., and Zhang, S. (2024). Recent progress on the application of MOFs and their derivatives in adsorbing emerging contaminants. *Sep. Purif. Technol.* 350, 127955. doi:10.1016/j.seppur.2024.127955

Shen, Y., Li, Q., and Qian, J. (2026). Metal-organic frameworks for sustainable water management: rational design, sorption mechanisms, and emerging applications. *Coord. Chem. Rev.* 557, 217729. doi:10.1016/j.ccr.2026.217729

Slater, B., Wong, S.-O., Duckworth, A., White, A. J. P., Hill, M. R., and Ladewig, B. P. (2019). Upcycling a plastic cup: one-pot synthesis of lactate containing metal organic frameworks from polylactic acid. *Chem. Commun.* 55, 7319–7322. doi:10.1039/C9CC02861G

Sompornpailin, D., Ratanatawanate, C., Chantanavorakunchai, N., and Punyapalakul, P. (2021). Effects of electrolytes and fractionated dissolved organic matter on selective adsorption of pharmaceuticals on terephthalic acid-based metal-organic frameworks. *Environ. Res.* 196, 110335. doi:10.1016/j.envres.2020.110335

Sutherland, C. (2025). Exploring the state-of-the-art in metal-organic frameworks for antibiotic adsorption: a review of performance, mechanisms, and regeneration. *Environ. Toxicol. Chem.* 44, 880–894. doi:10.1093/etojnl/vgaf009

Thakur, S., and Bharti, S. (2025). Recent progress in metal–organic frameworks based nanocomposites for antibiotic removal from water: an in-depth review. *Environ. Sci. Pollut. Res.* 33, 5211–5241. doi:10.1007/s11356-025-36155-3

Vellingiri, K., Tsang, D. C. W., Kim, K.-H., Deep, A., Dutta, T., and Boukhvalov, D. W. (2018). The utilization of zinc recovered from alkaline battery waste as metal precursor in the synthesis of metal-organic framework. *J. Clean. Prod.* 199, 995–1006. doi:10.1016/j.jclepro.2018.07.233

Wang, N., Wei, Y., Chang, M., Liu, J., and Wang, J.-X. (2022). Macro-meso-microporous metal–organic frameworks: template-assisted spray drying synthesis and enhanced catalysis. *ACS Appl. Mater Interfaces* 14, 10712–10720. doi:10.1021/acsami.1c23297

Wei, F., Gong, J., Ren, Q., Yu, X., Wang, Y., Chen, H., et al. (2024). Preparation of Zn/Zr-MOFs by microwave-assisted ball milling and adsorption of lomefloxacin hydrochloride and levofloxacin hydrochloride in wastewater. *Environ. Res.* 252, 118941. doi:10.1016/j.envres.2024.118941

Weng, Z., Mei, K., Sun, B., Gou, C., Liu, J., Dai, X., et al. (2025). Citric acid and polyethylene glycol modified Na-cyclodextrin MOFs for efficient antibiotic removal and in-depth investigation of adsorption mechanisms. *Environ. Res.* 286, 122726. doi:10.1016/j.envres.2025.122726

Weng, Z., Sun, B., Mei, K., Gou, C., Liu, J., Dai, X., et al. (2026). Ultrasound-assisted rapid synthesis of green Na-cyclodextrin MOFs modified with malic acid and polyethylene glycol, and investigation of their adsorption mechanism. *Sustain Chem. Pharm.* 49, 102287. doi:10.1016/j.scp.2025.102287

Worku, A. K., Ayele, D. W., Teshager, M. A., Omar, M., Yerkrang, P. P., Elgaddafi, R., et al. (2025). Recent advances in wastewater treatment technologies: innovations and new insights. *Energy Rev.* 4, 100164. doi:10.1016/j.enrev.2025.100164

Wu, Z., Shao, X., and Wang, Q. (2025a). Antibiotics and antibiotic resistance genes in the environment: dissemination, ecological risks, and remediation approaches. *Microorganisms* 13, 1763. doi:10.3390/microorganisms13081763

Wu, J., Zhang, Q., He, Z., Zhang, Y., Chen, Y., Liu, H.-B., et al. (2025b). Efficient adsorption and sensitive detection of tetracycline antibiotics based on pyrene-functionalized Cu-MOF. *J. Environ. Chem. Eng.* 13, 119277. doi:10.1016/j.jece.2025.119277

Xu, L., Chen, P., Zhang, X., Lan, D. L., Liu, Y., Lai, W., et al. (2024). Synthesis of Zr-based metal-organic framework/MWCNTs composite for adsorption of enrofloxacin from aqueous solution. *Sep. Purif. Technol.* 334, 126004. doi:10.1016/j.seppur.2023.126004

Yan, B., Wang, C., Feng, Q., Niu, C., Zhao, W., Feng, M., et al. (2026). Deciphering the flocculation mechanism of cellulose - modified polymers for antibiotic and co-pollutant removal: structural determinants from structure-activity relationships. *J. Environ. Sci.* 164, 644–655. doi:10.1016/j.jes.2025.08.028

Yang, Z., Cao, J., Chen, Y., Li, X., Xiong, W., Zhou, Y., et al. (2019). Mn-doped zirconium metal-organic framework as an effective adsorbent for removal of tetracycline and Cr(VI) from aqueous solution. *Microporous Mesoporous Mater.* 277, 277–285. doi:10.1016/j.micromeso.2018.11.014

Yang, F., Du, M., Yin, K., Qiu, Z., Zhao, J., Liu, C., et al. (2022). Applications of metal-organic frameworks in water treatment: a review. *Small* 18, 2105715. doi:10.1002/smll.202105715

Yi, X.-H., Chu, H.-Y., Wang, C.-Y., Ren, H., Zhou, L., Zhao, Y., et al. (2026). Metal-organic frameworks for clean water. *Chin. Chem. Lett.* 37, 112243. doi:10.1016/j.cclet.2025.112243

Yuan, Y., Ju, H., Tong, X., Xu, F., Zhang, J., and Gin, K. Y.-H. (2025). A comprehensive framework of health risk assessment for antibiotic resistance in aquatic environments: status, progress, and perspectives. *J. Hazard Mater* 497, 139748. doi:10.1016/j.jhazmat.2025.139748

Yuan, Y., Sang, Q., Liu, H., Yang, Z., Xie, C., and Ren, S. (2026). Metal-organic framework-hybridized immobilized laccase for the efficient degradation of industrial wastewater pollutants. *Ecotoxicol. Environ. Saf.* 309, 119668. doi:10.1016/j.ecoenv.2025.119668

Yue, J., Zheng, Q., Ding, S., Yin, Y., Zhang, X., Wang, L., et al. (2024). Cu–Co bimetallic organic framework as effective adsorbents for enhanced adsorptive removal of tetracycline antibiotics. *Sci. Rep.* 14, 17607. doi:10.1038/s41598-024-67986-8

Yusuf, M., Naim, Z., Jannat, M. M., Islam, M., Sayeem, N. R., Islam, M. M., et al. (2026). Unraveling the potential of metal–organic frameworks for antibiotic remediation: from molecular interactions to real-world challenges. *Chemosphere* 394, 144786. doi:10.1016/j.chemosphere.2025.144786

Zhan, G., Ng, W. C., Lin, W. Y., Koh, S. N., and Wang, C.-H. (2018). Effective recovery of vanadium from oil refinery waste into vanadium-based metal–organic frameworks. *Environ. Sci. Technol.* 52, 3008–3015. doi:10.1021/acs.est.7b04989

Zhang, D., Yang, S., Yang, C., Chen, Y., Hu, R., Xie, Y., et al. (2022). New insights into the interaction between dissolved organic matter and different types of antibiotics, oxytetracycline and sulfadiazine: multi-Spectroscopic methods and density functional theory calculations. *Sci. Total Environ.* 820, 153258. doi:10.1016/j.scitotenv.2022.153258

Zhang, Z., Zhang, H., Tian, D., Phan, A., Seididamyeh, M., Alanazi, M., et al. (2024). Luminescent sensors for residual antibiotics detection in food: recent advances and perspectives. *Coord. Chem. Rev.* 498, 215455. doi:10.1016/j.ccr.2023.215455

Zhang, X., Fang, J., Xu, J., Zhang, Y., Chen, Y., and Xiang, W. (2026). Integrated adsorption and photo-Fenton catalysis for efficient water decontamination using a scalable and recyclable waste-derived MOF-Cotton composite. *Sep. Purif. Technol.* 389, 136900. doi:10.1016/j.seppur.2026.136900

Zhao, X., Zhang, C., Liu, B., Zhao, H., Gao, X., Wang, Y., et al. (2023). Resource mining from stainless steel pickling wastewater to produce metal-organic frameworks. *Resour. Conserv. Recycl* 188, 106647. doi:10.1016/j.resconrec.2022.106647

Zhao, S., Lv, Y., Liu, X., Xiao, M., and Lei, S. (2026). Synergistic electronic modulation and morphological engineering of CoFe-MOF via Ni/Mo co-doping for efficient alkaline hydrogen evolution. *Chem. Phys.* 607, 113189. doi:10.1016/j.chemphys.2026.113189

Zheng, M., Shao, Y., Ma, F., Li, W., and Guo, M. (2025). Adsorption of antibiotics in medical wastewater by MOF-Based hydrogel composites: a comprehensive review. *J. Water Process Eng.* 76, 108268. doi:10.1016/j.jwpe.2025.108268

Zhou, Q., and Liu, G. (2020). Urea-functionalized MIL-101(Cr)@AC as a new adsorbent to remove sulfacetamide in wastewater treatment. *Ind. Eng. Chem. Res.* 59, 12056–12064. doi:10.1021/acs.iecr.0c01037

Zong, Y., Ma, S., Gao, J., Xu, M., Xue, J., and Wang, M. (2021). Synthesis of porphyrin Zr-MOFs for the adsorption and photodegradation of antibiotics under visible light. *ACS Omega* 6, 17228–17238. doi:10.1021/acsomega.1c00919

Zou, Y., Yang, W., Fu, T., Chen, Y., Yang, S., Wang, B., et al. (2026). Synergistic removal of tetracycline and cadmium in real wastewater using KHCO3-Modified biochar derived from agricultural waste: mechanism and engineering application. *J. Environ. Manage* 405, 129663. doi:10.1016/j.jenvman.2026.129663

Zu, S., Yang, Y., He, Y., Jin, J., and Du, Z. (2025). Defect engineering on carbon nanotubes electrodes for electrochemical removal of antibiotic resistance genes from aqueous environments. *Chem. Eng. J.* 522, 167419. doi:10.1016/j.cej.2025.167419