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Removal of pharmaceutical residues from aquatic systems using bimetallic metal–organic frameworks (BMOFs): a critical review

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In recent years, pharmaceuticals have become a major environmental issue due to their ongoing release and persistence in aquatic ecosystems, even at low concentrations. Among various solutions, bimetallic metal–organic frameworks (BMOFs) have attracted considerable attention. This is not only because of their tunable pore structures, large surface area, and excellent reactivity but also due to the incorporation of multiple metal ions, which enhance their ability to remove and degrade pharmaceutical residues. This review provides a detailed analysis of the advantages of BMOFs, introduces the occurrence of pharmaceutical residues and their toxic effects on the environment and humans, and, for the first time, explores their applications in removing pharmaceutical residues. Additionally, we discuss current challenges and future perspectives for BMOFs, aiming to advance their development and maximize their potential in environmental applications. We aim to provide detailed and meaningful insights to researchers in both materials science and environmental studies, thereby driving advancement in this interdisciplinary arena.

1 Introduction

Pharmaceutical pollutants are increasingly building up in both wastewater and freshwater systems, emerging as a significant environmental concern. Each year, around 300 million tons of pharmaceutical and industrial chemicals are discharged into natural water sources.[1] These micropollutants pose serious environmental hazards due to their non-biodegradable nature, high toxicity, and unique molecular structures.[2] Consequently, it is crucial to remove pharmaceuticals from wastewater to mitigate their harmful impacts on the environment, human health, and aquatic ecosystems.[3–5] Aquatic environments are continuously exposed to these persistent contaminants because wastewater treatment processes often fail to remove them completely. Pharmaceuticals are typically excreted *via* urine and feces as parent compounds, metabolites, or conjugates with glucuronic and sulfuric acids.[6] These substances enter aquatic ecosystems through the discharge of both treated and untreated wastewater.

The presence of pharmaceuticals in water can be linked to sources such as personal care products, waste from the pharmaceutical industry, hospital waste, and therapeutic drugs. The detection of trace amounts of pharmaceuticals and other xenobiotic compounds in treated drinking water raises significant public health concerns. Limited knowledge exists about the potential chronic health effects of long-term exposure to these compound mixtures through drinking water.[7–9] Therefore, addressing the removal of pharmaceuticals and other priority pollutants from wastewater before discharge has become a critical issue in environmental science. Significant efforts are needed to study this problem and mitigate its impacts effectively.

Recent studies emphasize photocatalytic degradation of pharmaceuticals for its affordability and eco-friendliness.[10] Materials such as metal oxides,[11] activated carbon,[12] , and metal–organic framework (MOF)-based nanoparticles have gained significant attention for their success in environmental treatment and protection.[13] MOFs, in particular, have drawn interest because of their tunable cavities, crystalline structures, high surface area, open framework, and diverse designs achieved through the combination of sources of metal ions and organic linkers.[14–20] Their high specific surface area and easily tunable porous structures make MOFs increasingly attractive for catalysis. In various applications, MOFs serve as catalysts and adsorbents for removing pollutants from wastewater.[21]

Compared to monometallic MOFs, bimetallic MOFs (BMOFs) offer enhanced and distinct functionalities. The incorporation of two metal ions increases the number of active sites, improving structural stability and catalytic efficiency due to synergistic interactions.[22] BMOFs are beneficial as multivalent metals provide extra redox-active sites.[23,24] Some BMOFs are created by altering the synthesis of existing MOFs to include a second metal ion. Ligand–metal interactions with similar electronic properties promote a single-phase bimetallic structure over separate monometallic compounds.[25] These

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heterometallic derivatives retain similarities to monometallic MOFs but often exhibit greater efficiency, unique properties, and stability.[26,27] Therefore, it is crucial to develop BMOFs with enhanced activity and to extensively explore their potential applications in removing residual pharmaceuticals.

Numerous research groups have explored different approaches to treating wastewater contaminated with pharmaceutical pollutants using various materials. This review summarizes the application of BMOFs in removing pharmaceutical pollutants, highlighting their efficiency as catalysts and adsorbents compared to other materials. Additionally, it examines the presence of pharmaceutical residues, their harmful environmental and human health effects, and the potential future applications of BMOFs in this field. To the best of our knowledge, no existing review comprehensively focuses on the removal of pharmaceutical pollutants specifically using BMOFs. Therefore, this paper aims to provide the most up-to-date insights into the use of BMOFs for treating pharmaceutical-contaminated wastewater, along with future research directions.

2 Occurrences of pharmaceutical residues and their toxic effects on the environment and humans

The widespread presence of xenobiotics in the environment has raised increasing concerns among urban authorities and health professionals due to their persistence and extended half-life. In recent decades, rapid industrial growth and urban expansion have led to the excessive depletion of essential natural resources.[28] The manufacturing processes for consumer goods involve several stages that release significant amounts of waste in various forms liquid, solid, or gaseous forms, all of which pose environmental hazards.[29,30] According to the World Health Organization (WHO), around 15% of hospital waste is categorized as infectious, making it both toxic and dangerous. Wastewater has long been a major reservoir for pharmaceutical compounds (PCs),[31] personal care products,[32] pesticides,[33] and other similar pollutants. The widespread presence of PCs in the environment can be attributed to their persistent release and slow transformation rates. Pharmaceutical manufacturing industries generate wastewater containing a diverse array of PCs, often with high chemical oxygen demand (COD) and occasionally elevated salinity levels.[34] The minimum concentrations of PCs in aquatic environments have been reported to range from ng L^{-1} to μg L^{-1}.[35] PCs are chemically stable and frequently referred to as micropollutants due to their complex fate and transport mechanisms. The physicochemical properties of these compounds play a critical role in determining the extent and severity of their contamination across various environmental media, including soil, water, and air. Between 2000 and 2015, global antibacterial medication usage increased by approximately 65%, and pharmaceutical consumption worldwide is projected to rise by 200% by 2030, compared to the 42 billion defined daily doses recorded in 2015.[36] The COVID-19 pandemic further accelerated the unprecedented use of drugs and medications.[37] Veterinary pharmaceuticals are often excreted directly onto the ground or into surface waters without undergoing treatment at wastewater treatment plants (WWTPs), making their management and monitoring significantly more difficult. The soil can serve as a major source of water pollution,[38] as many of these substances and their metabolites are water-soluble and are expelled through urine and feces.[39] In intensive livestock farming, these pharmaceuticals may enter the environment indirectly through the use of manure and slurry as fertilizers, potentially transferring to humans *via* the food chain. Additionally, pharmaceuticals utilized in fish farming are released directly into surface waters.[39]

The pharmaceuticals most commonly detected in water treatment effluents include steroids, antidepressants, antibiotics, antacids, analgesics, lipid-lowering agents, tranquilizers, anti-inflammatory drugs, antipyretics, beta-blockers, and stimulants. PCs tend to infiltrate host environments, such as surface water, groundwater, the cryosphere, and wastewater, eventually transforming into intermediate products through interactions with biotic and abiotic environmental components. These transformations, influenced by the reactivity and sensitivity of PCs, pose significant threats to aquatic ecosystems, including the development of resistant microbial species.[40]

Pharmaceuticals in the environment pose significant risks due to their ecological toxicity, physicochemical properties, and consumption rates. Risk assessments are essential as these substances can bioaccumulate, exhibit high water solubility, persist in ecosystems, and potentially cause harmful or carcinogenic effects on organisms.[41] Even trace levels of pharmaceutical residues in the environment can lead to acute and long-term impacts on microbes, plants, and animals. These effects may range from metabolic disruptions to hormonal imbalances and can harm non-target species.[42] The complexity of pharmaceutical mixtures in the environment means that certain compounds can cause severe damage even at very low concentrations, sometimes below detectable thresholds. Some pharmaceuticals exhibit effects on non-human species similar to their effects on humans,[43] as they are designed to interact with specific receptors in humans and animals, which may also exist in other organisms. This interaction can inhibit essential biological processes such as cell envelope synthesis, protein synthesis, and nucleic acid synthesis.[44] Pharmaceuticals in the environment severely impact a wide range of organisms, with environmentally beneficial microorganisms being more affected than aquatic organisms. Drugs like fluoxetine, diclofenac, ibuprofen, and carbamazepine exhibit carcinogenic effects even at low concentrations, and diclofenac specifically causes acute kidney failure in humans and other toxic effects. The "complex pools" of pharmaceutical mixtures in nature often have greater toxicity than individual compounds, yet chronic effects at ecological levels remain underreported.[45] Long-term, low-dose exposure to pharmaceuticals in drinking water and their entry into the food chain through plants, vegetables, and meat raise concerns about cumulative impacts on health. Wastewater effluents contain measurable concentrations of harmful pharmaceuticals, which pose risks to microbes, humans, and higher organisms. Studies show that while some aquatic species tolerate acute toxicity from drugs, phytoplankton and invertebrates are particularly

vulnerable. Chronic toxicity from compounds such as fluoxetine, carbamazepine, and 17 beta-estradiol presents significant risks to aquatic ecosystems, underscoring the need for further research on pharmaceutical mixtures and their ecological consequences.[46]

To reduce the presence of human and veterinary pharmaceuticals in the environment, it is essential to identify, test, and implement measures across short-, medium-, and long-term timeframes. Short-term measures to reduce pharmaceutical pollution focus on controlling emissions from production facilities, particularly in developing countries, and improving hygiene standards in hospitals and livestock farming to minimize infections and unnecessary antibiotic use. Efforts include promoting targeted antibiotic use, optimizing farm management practices, and exploring techniques such as manure treatment and biogas fermentation to reduce veterinary pharmaceutical residues. Mid-term measures emphasize developing environmentally friendly drugs, sustainable manufacturing processes, and formulations that minimize environmental impact. Long-term strategies involve designing eco-friendly pharmaceuticals through drug redesign and personalized medicine, supported by incentives for manufacturers to prioritize environmental sustainability. Additionally, enhanced monitoring, research on distribution pathways, and public education on proper drug disposal are essential across all timelines.[47] Fig. 1 provides a comprehensive overview of the various sources of pharmaceutical residues entering water systems, including industrial discharge, hospital waste, and agricultural runoff. It also illustrates their impact on wastewater contamination, soil pollution, potential health risks to humans, and adverse effects on aquatic ecosystems.

3 Bimetallic MOFs advancement over monometallic MOFs

MOFs are an emerging class of highly structured crystalline materials that form through the self-assembly of metal clusters and organic linkers *via* precisely coordinated bonds. Their unique physical and chemical properties have led to extensive applications in pollutant removal.[48,49] However, conventional MOFs encounter several challenges, including complex preparation processes, limited adsorption sites, structural instability, and the reliance on expensive metal salts. Research indicates that a high density of active metal sites significantly enhances pollutant adsorption capacity.[50] Compared to monometallic compounds (MMCs), BMOFs provide several benefits, including enhanced electrical conductivity, a greater number of active sites, adjustable electrochemical properties, and higher charge storage capacity. Integrating MOFs with other electrochemically active materials results in advanced composites with large specific surface areas, improved conductivity, and superior dispersion characteristics. Notably, certain BMOFs demonstrate increased electrocatalytic performance when exposed to light, making them suitable for use as photoelectrocatalysts.[51]

As a targeted strategy, BMOFs have garnered considerable attention across various fields.[52–55] These materials can be produced by altering the synthesis process of a particular MOF to incorporate a second metal ion. In this approach, the interaction between ligands and two metal ions with comparable electronic structures and charge distributions promotes the formation of a single-phase BMOF rather than a simple mixture of two separate MMCs.[23] Although these heterometallic derivatives share similarities with monometallic MOFs, they often demonstrate enhanced stability, efficiency, and other distinctive properties. This class of materials can function directly as electrode components or serve as templates or precursors in the fabrication of advanced composites.[56] BMOFs offer greater stability and efficiency than monometallic MOFs, enabling a dual-function mechanism or synergistic metal interactions.[26,57] The combination of two metal cations improves conductivity and enhances oxidation reactions, boosting electrocatalytic efficiency. It is evident that the incorporation of dual metal sites within a given MOF can result in superior electrochemical activity, attributable to the differing oxidation

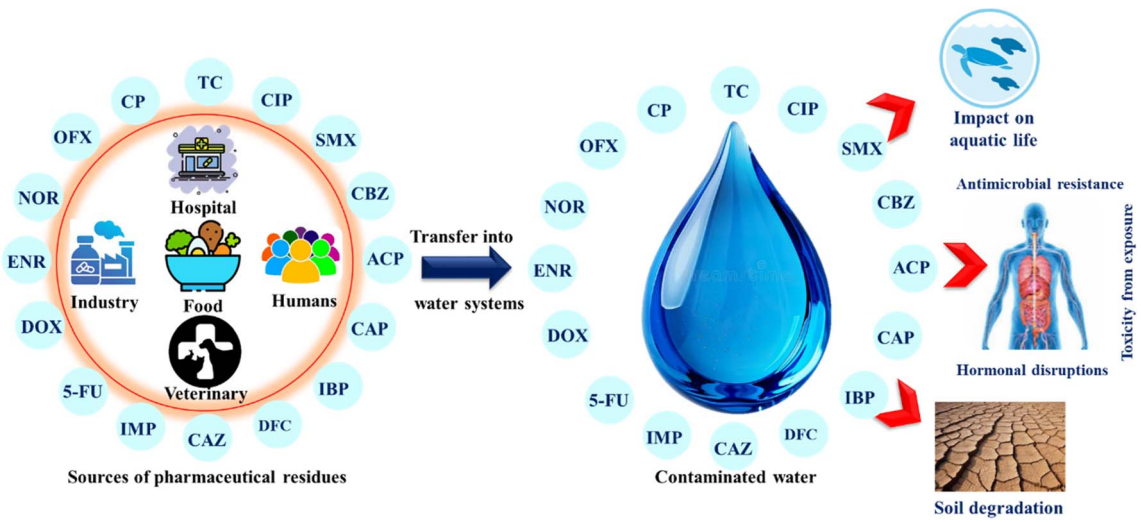

Fig. 1 Highlights the sources of pharmaceutical residues in water and their impact on wastewater, soil, humans, and aquatic life.

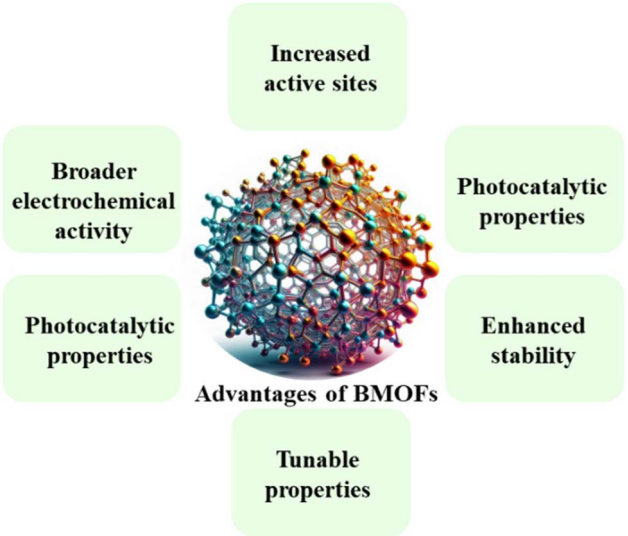

Fig. 2 The main unique characteristics of BMOFs.

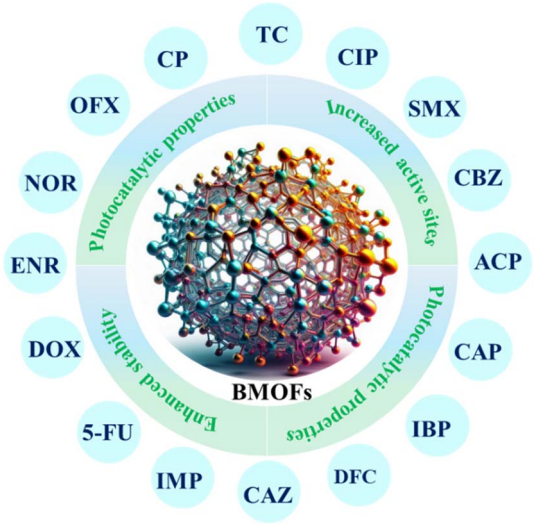

Fig. 3 Pharmaceutical residues removed using BMOFs.

potentials and associated electronic configurations.[58] Finally, facilitating multi-functional applications, BMOFs can serve multiple roles, such as functioning both as catalysts and adsorbents, making them suitable for integrated applications in environmental remediation.[59] Fig. 2 shows the main unique characteristics of BMOFs.

4 Applications

Bimetallic organic frameworks (BMOFs) and their derivatives demonstrate significant potential as alternative sorbents and catalysts for the efficient removal of a wide range of pharmaceuticals from aquatic solutions, including antibiotics, nonsteroidal anti-inflammatory drugs, and veterinary medications. The pharmaceuticals selected and reviewed in this study primarily include various classes, such as tetracycline (TC), ciprofloxacin (CIP), sulfamethoxazole (SMX), carbamazepine (CBZ), acetaminophen (ACP), chloramphenicol (CAP), ibuprofen (IBP), diclofenac sodium (DCF), ceftazidime (CAZ), imatinib (IMB), doxorubicin (DOX), 5-fluorouracil (5-FU), enrofloxacin (ENR), norfloxacin (NOR), moxifloxacin (MOX), cefoperazone (CP), sertraline, ofloxacin (OFX), and cefradine. As illustrated in Fig. 3.

4.1 Tetracycline removal

Since the discovery of antibiotics, bacterial infection-related diseases have been effectively managed. Among these, TC antibiotics, known as multifunctional broad-spectrum antibiotics, are widely utilized to treat bacterial infections in both humans and animals due to their ability to inhibit bacterial protein synthesis.[60] Additionally, TCs are used as feed additives in animal husbandry to promote animal growth. However, the overuse of antibiotics has led to a range of severe consequences.[61,62] Although TCs are biodegradable, their residual presence can cause selective genetic variations in microorganisms, resulting in the emergence of drug-resistant pathogens. Bacteria can acquire antibiotic resistance genes through mutations or gene transfer, and the exchange of these genes between agricultural soil bacteria and clinical pathogens often facilitates the spread of antibiotic resistance, giving rise to "superbugs". Recent studies have revealed that over 30 antibiotics, including various TCs and quinolones, have been detected in karst river systems, posing threats to non-target organisms across different trophic levels, such as algae, plants, bacteria, invertebrates, and fish.[63,64] However, the excessive use of TC can have significant impacts on human health, as TC residues may accumulate in foods such as meat and milk. Studies have shown that frequent consumption of TC can lead to liver damage and kidney issues in humans. Pregnant women are particularly vulnerable to TC-induced liver toxicity. Additionally, extensive data indicates that prolonged and repeated use of TC can negatively affect dental health by disrupting tooth growth and formation, as well as causing discoloration, turning teeth yellow.[65] BMOFs are promising porous materials for addressing environmental pollution caused by pharmaceuticals like TC, owing to their exceptional surface area, catalytic activity, and porous architecture. The following section reviews recent studies focused on the removal of TC, one of the most commonly used antibiotics, using BMOFs.

Chen *et al.* successfully synthesized bimetallic MOFs (MIL-53(Fe, Al)) for the efficient removal of TC from aqueous solutions. Their experiments on adsorption and photocatalysis revealed that a 3 : 2 molar ratio (40% MIL-53(Fe, Al)) yielded optimal performance. The adsorption process followed the Freundlich isotherm model and pseudo-second-order kinetics, with a maximum adsorption capacity of 402.033 mg g^{-1}. Under photocatalytic conditions, 10 mg of 40% MIL-53(Fe, Al) removed 94.33% of TC from a 70 mL solution (20 mg L^{-1}) within 50 minutes of irradiation, outperforming MIL-53(Fe) (71.39%) and MIL-53(Al) (81.82%). Additionally, the material demonstrated a strong adsorption-photocatalytic synergy, with the pseudo-first-order kinetic constant increasing by 3.11 times under

direct irradiation without prior dark adsorption.[66] In another study, Xia *et al.* developed a BMOF gel (JLUE-MOG-Fe/Y) for the adsorption of chlortetracycline hydrochloride (CTC) from water. This material exhibited exceptional stability, adaptability, and recyclability, achieving a remarkable adsorption capacity of 584.83 mg g^{-1} at 25 °C.[67] Similarly, Zhang *et al.* designed transition metal/nitrogen-codoped hierarchically porous carbons (MNHCs) by pyrolyzing bimetallic ZIFs to enhance the adsorption of TC. The optimized MNHC, synthesized at 1000 °C with a 2% Fe/(Fe + Zn) molar ratio, featured a large specific surface area (920.73 m^2 g^{-1}), a hierarchical pore structure, high nitrogen content, and abundant Lewis acid sites. These properties significantly improved TC adsorption affinity and reduced diffusion resistance, leading to superior performance.[68]

Zhang *et al.* developed a novel Fe/Mn-MOF combined with a SnS_2 Z-scheme heterojunction photocatalyst through self-assembly. Leveraging the synergistic effects of the interfacial heterojunction, the photocatalyst demonstrated exceptional catalytic performance. With the aid of a persulfate-based advanced oxidation process, it achieved a degradation efficiency of nearly 91.4% for TC.[69] Lastly, Liu *et al.* fabricated Fe-doped zeolitic imidazolate frameworks-8 loaded cellulose (Fe/ZIF-8@cellulose) aerogels. The incorporation of Fe into ZIF-8 resulted in a maximum TC adsorption capacity of 1359.2 mg g^{-1}, surpassing the performance of previously reported ZIF-8-based polysaccharide adsorbents.[70]

Table 1 provides a summary of studies that have employed BMOFs for TC removal.

4.2 Ciprofloxacin removal

CIP one of the most commonly used second-generation quinolones, is widely employed in the treatment of bacterial infections.[100] However, CIP is often released into the environment through wastewater discharges and is frequently detected in various aquatic ecosystems. Wastewater from pharmaceutical industries and hospitals is particularly concerning, as it can contain extremely high levels of CIP contamination, reaching up to 31 mg L^{-1}.[101,102] Consequently, developing environmentally and economically sustainable methods to remove CIP from water is essential to mitigate public health risks associated with the emergence of antibiotic resistance in the environment.

Li *et al.* successfully synthesized a novel hetero-photo-Fenton (PF) catalyst, consisting of dual MOF-derived Fe–Zr oxide embedded in porous carbon skeleton. This hybrid photocatalyst, featuring a high surface area, well-developed porous structures, strong light absorption, and a narrow band gap, exhibited exceptional photo-Fenton activity, achieving around 99.1% degradation of CIP. Additionally, the catalyst system performed well in treating real water matrices.[103]. Lastly, Zhang *et al.* synthesized Cu/Ni-MOF for the targeted degradation of CIP in advanced oxidation processes (AOPs). The specific

Table 1 Removal of TC using BMOFs

Types of BMOFs	Method	Catalyst dosage	Initial concentration	Performance%	Ref.
Bi/Ni-MOF	Degradation	30 mg	10 mg L^{-1}	93.6	71
Fe/Ni-MOF	Degradation	20 mg	20 mg L^{-1}	95.76	72
Co/Zn-ZIF	Adsorption, degradation	60 mg L^{-1}	20 mg L^{-1}	89.54	73
Sn/Bi-MOF	Degradation	40 mg	20 mg L^{-1}	96.2	74
Ag/Bi-MOF	Degradation	30 mg	20 mg L^{-1}	83	75
Fe/Mn-MOF	Degradation	0.2 g L^{-1}	20 mg L^{-1}	90.95	76
Fe/Co-MOF	Degradation	50 mg/L	50 mg L^{-1}	91.76	77
Co/MIL-68(In)-NH_2	Degradation	0.6 g L^{-1}	10 mg L^{-1}	90.1	78
Fe/Co-MOF	Degradation	0.2 g L^{-1}	50 mg L^{-1}	99	79
Nb/Co-MOF	Degradation	0.2g L^{-1}	40 mg L^{-1}	97.8	80
Fe/Co-MOF	Adsorption	20 mg	100 mg L^{-1}	98	81
Fe/Co-MOF	Degradation	0.125 g L^{-1}	50 mg L^{-1}	90	82
Fe/Co-MOF	Adsorption, degradation	30 mg, 10 mg	70 mg L^{-1}, 20 mg L^{-1}	87.5, 91	83
Ni/Fe-MOF	Adsorption	1 g L^{-1}	400 mg L^{-1}	—	84
Fe/Bi-MOF	Degradation	0.5 g L^{-1}	20 mg L^{-1}	99.9	85
Fe/Co-MOF	Degradation	0.1 g L^{-1}	10 mg L^{-1}	100	86
Zr/Cu-MOF	Degradation	40 mg	—	94	87
Ni/Ti-MOF	Degradation	0.2 g L^{-1}	50 mg L^{-1}	83	88
Zn/Fe-MOF	Adsorption	10 mg	300 mg L	—	89
Co/Cu-MOF	Degradation	0.1 g L^{-1}	20 mg L^{-1}	98.7	90
Fe/Zn-ZIFs	Degradation	0.4 g L^{-1}	50 mg L^{-1}	92	91
Cu/Co-MOFs	Adsorption	50 mg	30 ppm	93.7	92
Fe/Co-MOF	Adsorption	—	20 mg L	—	93
Cu/Fe-ZIF-8	Adsorption	100 mg L	100 mg L	87.2	94
Zn/Cu-MOF-74	Adsorption	15 mg	30 mg L^{-1}	—	95
Zr/Fe-MOF	Degradation	10 mg	50 mg L^{-1}	87	96
Zn/Cu-MOF	Adsorption	20 mg	20 mg L^{-1}	96.55	97
Fe/Cu-MOF	Degradation	0.6 g L^{-1}	20 mg L^{-1}	93	98
Fe/Co-MOF	Degradation	10 mg	20 mg L^{-1}	93.34	99

Table 2 Removal of CIP using BMOFs

Types of BMOFs	Method	Catalyst dosage	Initial concentration	Performance%	Ref.
Fe/Cu or Mn-MOF	Degradation	0.1 g L^{-1}	20 mg L^{-1}	88.96	105
Cu/Co-MOF	Degradation	25 mg	20 mg L^{-1}	90	106
Ti/Bi-MOFs	Degradation	20 mg	10 mg L^{-1}	93.3	107
Zn/Co-ZIF	Degradation	0.1 g L^{-1}	20 mg L^{-1}	90	108
Zn/Co-ZIF	Adsorption	0.5 g L^{-1}	—	85.30	109
In/Cu-MOF	Degradation	2 mg	15 mg L^{-1}	81.70	110
Ce/Zr-MOF	Degradation	20 mg	20 ppm	90.8	111
Fe/Cu-MOF	Adsorption, degradation	0.1 g L^{-1}	15 mg L^{-1}	74.48, 57.88	112
Fe/Mn-MOF	Degradation	5 mg	20 mg L^{-1}	98.3	113

recognition sites on Cu/Ni-MOF, enabled by electrostatic interactions and functional group binding with CIP, provided excellent selective recognition (Q_{max} = 14.82 mg g^{-1}). This allowed active radicals to efficiently target and degrade the contaminants.[104] Table 2 provides an overview of studies that employed BMOFs for CIP removal.

4.3 Sulfamethoxazole removal

SMX, a widely used antimicrobial, treats infections and supports livestock growth, with global consumption exceeding 84 240 tons annually.[114] Unfortunately, only a small portion of SMX is metabolized or absorbed by living organisms, with approximately 70% being excreted through feces or urine and subsequently discharged into water. However, due to the limitations of current wastewater treatment technologies in effectively removing such antibiotics, significant concentrations of SMX have been detected in the effluent from medical industries, municipal sewage systems, and livestock farms.[115] These SMX residues not only contribute to bacterial resistance and reduce the efficacy of drug treatments but also pose risks to ecosystems and human health.[116] Therefore, it is crucial to develop more effective treatment methods to eliminate SMX.

Tang *et al.* synthesized Fe/Cu-MOF and evaluated its performance in the catalytic degradation of SMX. The BMOF system demonstrated high efficiency for SMX degradation across a broad pH range (4.0–8.6). At an initial pH of 5.6, the BMOF catalyst achieved complete removal of SMX (20 mg L^{-1}) within 120 minutes, outperforming monometallic Fe-MOF and Cu-MOF catalysts.[117] In addition, Wu *et al.* utilized Mn/Fe-MOFs as a cathode in a heterogeneous electro-Fenton system to effectively remove SMX. At pH 3 and a current of 30 mA, the system achieved 96% SMX degradation within 90 minutes, with 12.09 mg L^{-1} of H_2O_2 and 0.21 mM of ·OH detected, highlighting its efficiency.[118] Similarly, Zhou *et al.* developed a novel Fe/Co-MOF for SMX removal in an AOP. The Fe/Co-MOF demonstrated excellent catalytic performance in activating peracetic acid (PAA) for SMX degradation under neutral conditions. While increasing PAA concentration improved SMX removal, varying the Fe/Co-MOF dosage from 0.05 to 0.2 g L^{-1} had minimal impact on degradation efficiency.[119] Furthermore, Xie *et al.* introduced a self-assembly strategy to synthesize highly dispersed Co/Fe bimetallic carbon cages ($CoFe_{50}$@C) through the thermal transformation of Fe-doped dual MOFs. Leveraging the well-dispersed Co/Fe species, synergistic effects, and enhanced carbon graphitization, $CoFe_{50}$@C achieved 98% SMX removal within 180 minutes.[120] Guo *et al.* proposed a dual-MOF-assisted strategy to construct core–shell magnetic Fe_3O_4@ZIFs composites for PAA activation. The Fe_3O_4@ZIFs exhibited superior activity, achieving 99.3% SMX degradation within 30 minutes, outperforming similar materials.[121] Lastly, Peng *et al.* synthesized a stable Fe/Co-MOF to activate peroxymonosulfate (PMS) for SMX degradation. Fe/Co-MOF demonstrated exceptional catalytic performance, achieving 100% degradation of 5 mg per L SMX within 30 minutes.[122]

4.4 Carbamazepine removal

CBZ is a commonly used pharmaceutical compound found in drugs and PPCPs.[123] It is a significant micropollutant due to its widespread use and high detection rate in natural water sources. After CBZ is administered to humans, various derivatives are formed through *in vivo* metabolism and environmental degradation of the parent compound. These derivatives are often more toxic and harder to degrade than CBZ itself, making it essential to study their environmental behavior and develop effective removal methods. Widely used in the treatment of epilepsy and bipolar disorder, CBZ has a high annual consumption rate.[124] Research indicates that prolonged exposure to CBZ can have toxic effects on the central nervous and digestive systems, impair embryonic cell development, and affect blood cell levels.[125] As a result, there is an urgent need to develop effective treatment technologies to eliminate CBZ and its derivatives from aquatic environments.

Several studies have explored efficient catalysts for CBZ degradation. Zheng *et al.* successfully developed a highly efficient Mn-doped MIL-53 (Fe) precursor at high temperatures. The FeMn@C-800/2 catalyst demonstrated the highest catalytic performance for CBZ degradation, achieving an apparent first-order reaction rate 8.9 and 17.8 times greater than Fe@C-800 and Mn@C-800, respectively, under optimal conditions (catalyst dosage: 50 mg L^{-1}, pH: 4.0).[126] Roy *et al.* synthesized NH_2-MIL-125(Ti)@MIL-53(Fe/Co) (AMIL@MIL). This catalyst facilitated CBZ mineralization in aqueous solution *via* PMS activation under visible light, completely degrading CBZ (10 mg L^{-1}) within one hour using 0.05 g L^{-1} of the composite containing 10 wt% NH_2-MIL-125(Ti) and 0.25 g L^{-1} of PMS.[127] Thai *et al.* introduced MIL-100@ZIF-67@MXene, a novel metallic MOF composite anchored on MXene nanosheets, designed for enhanced CBZ degradation and PMS activation. Their study

thoroughly investigated the composite's efficiency, reaction parameters, and mechanisms, revealing that the MIL-100@ZIF-67@MXene/PMS system reduced CBZ by 95% within 30 minutes under neutral pH conditions.[128] Huang *et al.* developed Co/N–PC-*T* precursors using solvent heating and immersion methods, followed by simple pot calcination of Co/Zn-MOF to obtain Co/N–PC-*T*. These catalysts were employed for PMS activation and pollutant degradation, with Co/N–PC-800 exhibiting exceptional catalytic performance. When used for PMS activation, Co/N–PC-800 achieved over 98% CBZ degradation in 30 minutes.[129]

4.5 Acetaminophen removal

ACP a pharmaceutical and PPCP, is one of the most widely used painkillers and has been detected in sewage, sewers treatment plants, and even drinking water due to its extensive use.[130] It is also commonly utilized as an analgesic and antipyretic and serves as a key component in anti-flu medications worldwide.[131] ACP in water systems poses significant risks to aquatic life and human health. Research highlights its environmental impact and associated health hazards, including liver failure, gastrointestinal disorders, and liver necrosis.[132] Consequently, there is an urgent need to develop effective methods to remove ACP from wastewater before it is released into aquatic environments.

Alrefaee *et al.* effectively removed pharmaceutical contaminants from wastewater using a novel adsorbent, La/Th-MOF. This material consists of stacked nanorods of 2-methyl imidazole coordinated with lanthanum and thorium. It demonstrated an impressive maximum adsorption capacity of 339.75 mg g^{-1} for ACT, highlighting its potential as a cost-effective and efficient adsorbent for wastewater treatment. The study found that pH levels significantly influence ACT adsorption, with optimal performance occurring in an acidic environment (pH 5) at an adsorbent dosage of 0.02 g.[133] Pattappan *et al.* synthesized Fe/Co-MOF, which exhibited enhanced light absorption in the visible spectrum and a bandgap energy of 1.73 eV. Photoluminescence analysis revealed a lower charge carrier recombination rate in Fe/Co-MOF compared to bare Fe- or Co-MOFs. The Fe/Co-MOF achieved a maximum AAP conversion rate of 97.4% (rate constant 0.031 min^{-1}) in 180 minutes, outperforming Fe-MOF (66%) and Co-MOF (73%). A scavenger study identified superoxide anion radicals as the primary agents responsible for AAP and 2,4-D degradation. The catalyst maintained its stability over five recycles without any decline in AAP degradation efficiency. Fe/Co-MOF photodegraded 2,4-D by 79.8%.[134] Li *et al.* successfully synthesized Fe/Co-MOF by co-doping MIL-101(Fe). This material achieved complete (100%) APAP degradation within 15 minutes at a Fe/Co-MOF concentration of 0.05 g L^{-1} and a PMS concentration of 0.8 mmol L^{-1}. Notably, the degradation process remained effective across a wide pH range (3–9), demonstrating the material's versatility in various wastewater treatment conditions.[135]

4.6 Chloramphenicol removal

CAP is a widely used antibiotic for treating bacterial infections and is frequently detected in surface water, wastewater effluents, groundwater, and soil environments.[136,137] CAP is known for its blood toxicity, embryotoxicity, and potent immunosuppressive effects, which can also disrupt the physiological functions of plants, animals, and microorganisms.[138] As a result, there is an urgent need to develop effective technologies and strategies to eliminate CAP.

Xue *et al.* developed a BMOF derivative to *in situ* modify bulk CA (Ce/Fe@C-CA), creating a bifunctional composite cathode for CAP degradation in the heterogeneous EF process. This composite cathode demonstrated high CAP degradation efficiency of 94.89% was achieved.[139] Lei *et al.* synthesized a novel nitrogen-doped Fe/Ni-MOF derivative for efficient ionizing radiation-catalytic degradation of CAP. Compared to single electron beam (EB) irradiation, the radiation-catalytic process enhanced the degradation rate constant by 2.8 times and improved the total organic carbon (TOC) removal rate by 21.2 times. Notably, a synergistic effect between Fe and Ni in their valence states was observed, with Fe^{2+} playing a crucial role in promoting hydroxyl radical production during the radiation-catalytic process.[140]

4.7 Ibuprofen removal

IBP is a widely used non-steroidal anti-inflammatory drug commonly prescribed for pain relief, fever reduction, and inflammation management.[141] It has proven highly effective in treating rheumatoid arthritis. Due to its extensive global consumption, IBP is frequently detected in freshwater sources, raising concerns about its potential ecological effects. Studies suggest it may have long-term adverse impacts on aquatic life.[142,143] Additionally, ibuprofen has been identified as an indicator of wastewater contamination.[144] Given its threat to aquatic organisms and the stability of ecosystems, it is crucial to remove this pollutant from wastewater before it is released into the environment.

Li *et al.* successfully synthesized Mn-MIL-53(Fe) by adjusting the Mn doping ratio. Using the UV/Mn-MIL-53(Fe)/PMS process, IBP removal reached 79.7% within 30 minutes at a Mn-to-Fe molar ratio of 1.0, with a reaction rate constant 26.9% higher than the undoped counterpart.[145] Similarly, Thai *et al.* developed an advanced bimetallic catalyst, Mn/ZIF-67@GO, for efficient IBP degradation. The Mn/ZIF-67@GO/PMS system exhibited outstanding catalytic performance, achieving 98% degradation of a 0.05 mM IBP solution in just 15 minutes. Additionally, the system proved versatile, successfully removing over 80% of other tested antibiotics.[146]

4.8 Diclofenac sodium removal

DCF, a widely used anti-inflammatory drug, is consumed globally in large quantities. Its high water solubility and polarity contribute to its frequent detection in wastewater, natural water sources, and even drinking water.[147] Prolonged exposure to DCF poses potential health risks, including hemodynamic changes and thyroid tumors.[148] As a result, increasing attention has been directed toward the removal of DCF from aqueous solutions.

Wang *et al.* successfully developed a novel adsorbent based on a Ni/Co-MOF. Kinetic and isothermal analyses revealed that

Table 3 Removal of pharmaceutical residues using BMOFs

Types of BMOFs	Name of residues	Method	Catalyst dosage	Initial concentration	Performance%	Ref.
Fe/Cu-MOF	CAZ	Degradation	—	5 mg L^{-1}	99.5	151
Fe/Ni-MOF	IMB	Adsorption, degradation	99 mg, 50 mg	81 mg L^{-1}, 50 mg L^{-1}	89.12, 92.17	152
Co/Fe-MOF	DOX, 5-FU	Adsorption	0.5 g L^{-1}	10 mg L^{-1}	87.97	153
Co/Cu-MOF	DOX	Degradation	5 mg	20 mg L^{-1}	80	154
Fe/Ni-MOF	ENR	Degradation	2 mg	30 mg L^{-1}	95	155
Fe/Cu-MOF	ENR	Degradation	20 mg L^{-1}	20 mg L^{-1}	90	156
Fe/Cu-MOF	NOR	Degradation	—	20 mg L^{-1}	99.48	157
Co/Zn-MOF	NOR	Adsorption	0.8 g L^{-1}	50 mg L^{-1}	—	158
NI/Mo-MOF	MOX	Degradation		2 mg L^{-1}	95	159
Ni/Co-MOF	CP	Degradation	0.25 g L^{-1}	46.5 mg L^{-1}	88.9	160
Co/Ni-MOF	Sertraline	Degradation	75 mg	117 mg L	97.19	161
Fe/Mn-MOF	OFX	Degradation	0.1 g L^{-1}	5 mg L^{-1}	81.85	162
Fu/Cu-MOF	OFX	Degradation	30 mg	30 mg L^{-1}	100	163
Zr/Co-MOF	Cefradine	Adsorption	2 mg	20 mg L^{-1}	95	164

the adsorption behavior of Ni/Co-BTC MOF for DCF closely followed the Langmuir and pseudo-second-order models, with a maximum adsorption capacity of 343.05 mg g^{-1}.[149] Similarly, He *et al.* synthesized an environmentally friendly Bi–Zr bimetallic MOF derived from plant-based materials and investigated its adsorption properties for typical pharmaceutical and PPCPs, specifically DCF.[150]

4.9 Removal of other pharmaceutical residues

BMOFs have been used to remove various pharmaceutical residues, as summarized in Table 3, including ceftazidime (CAZ), imatinib (IMB), doxorubicin (DOX), 5-fluorouracil (5-FU), enrofloxacin (ENR), norfloxacin (NOR), moxifloxacin (MOX), cefoperazone (CP), sertraline, ofloxacin (OFX), and cefradine. Table 3 presents a summary of studies that employed BMOFs for various pollutant removal.

5 Conclusion and prospect

The presence and behavior of pharmaceuticals in the environment, particularly in aquatic systems, have been a significant focus of scientific research over the past two decades. Due to their biologically active, lipophilic nature and resistance to biodegradation, pharmaceuticals can accumulate and persist in the environment, posing risks even at low concentrations. To address this issue, BMOFs have emerged as promising materials for removing pharmaceutical residues. These materials function as both adsorbents and catalysts, offering unique advantages such as high surface area, exceptional porosity, customizable pore sizes, and structural tunability. Compared to monometallic compounds, BMOFs exhibit enhanced electrical conductivity, greater charge capacity, increased active sites, and adjustable chemical reactivity. While BMOFs demonstrate excellent adsorption and degradation capabilities, challenges remain in achieving consistent pore structures, durable designs, and stable functional groups. Furthermore, ecotoxicological analyses and life-cycle assessments are essential for evaluating the environmental impact of BMOFs, particularly in large-scale applications. Despite these challenges, BMOFs and their composites hold significant potential as advanced materials for pharmaceutical removal, contributing to sustainable environmental practices.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Conflicts of interest

There are no conflicts to declare.

References

1 J. Ouyang, L. Zhou, Z. Liu, J. Y. Y. Heng and W. Chen, Biomass-derived activated carbons for the removal of pharmaceutical mircopollutants from wastewater: a review, *Sep. Purif. Technol.*, 2020, **253**, 117536.
2 C. R. Ohoro, A. O. Adeniji, A. I. Okoh and O. O. Okoh, Distribution and chemical analysis of pharmaceuticals and personal care products (PPCPs) in the environmental systems: a review, *Int. J. Environ. Res. Public Health*, 2019, **16**(17), 3026.
3 M. J. Gallardo-Altamirano, P. Maza-Márquez, J. M. Peña-Herrera, B. Rodelas, F. Osorio and C. Pozo, Removal of anti-inflammatory/analgesic pharmaceuticals from urban wastewater in a pilot-scale A_2O system: linking performance and microbial population dynamics to operating variables, *Sci. Total Environ.*, 2018, **643**, 1481–1492.
4 E. F. Lessa, M. L. Nunes and A. R. Fajardo, Chitosan/waste coffee-grounds composite: an efficient and eco-friendly adsorbent for removal of pharmaceutical contaminants from water, *Carbohydr. Polym.*, 2018, **189**, 257–266.
5 Y.-L. Lin and B.-K. Li, Removal of pharmaceuticals and personal care products by *Eichhornia crassipes* and *Pistia stratiotes*, *J. Taiwan Inst. Chem. Eng.*, 2016, **58**, 318–323, DOI: 10.1016/j.jtice.2015.06.007.

6 M. Gros, M. Petrović, A. Ginebreda and D. Barceló, Removal of pharmaceuticals during wastewater treatment and environmental risk assessment using hazard indexes, *Environ. Int.*, 2010, **36**(1), 15–26.
7 P. E. Stackelberg, E. T. Furlong, M. T. Meyer, S. D. Zaugg, A. K. Henderson and D. B. Reissman, Persistence of pharmaceutical compounds and other organic wastewater contaminants in a conventional drinking-water-treatment plant, *Sci. Total Environ.*, 2004, **329**(1–3), 99–113.
8 M. Klavarioti, D. Mantzavinos and D. Kassinos, Removal of residual pharmaceuticals from aqueous systems by advanced oxidation processes, *Environ. Int.*, 2009, **35**(2), 402–417, DOI: **10.1016/j.envint.2008.07.009**.
9 C. de A. Bastos and M. A. L. de Oliveira, Quantitative determination of acetaminophen, phenylephrine and carbinoxamine in tablets by high-performance liquid chromatography, *Quim. Nova*, 2009, **32**, 1951–1955.
10 A. H. Hirad, Photocatalyst based on composite of trimetallic metal-organic frameworks for efficient visible-light degradation in pharmaceutical pollutants abatement and process modeling using RSM, *Surf. Interfaces*, 2024, **52**, 104909, DOI: **10.1016/j.surfin.2024.104909**.
11 X. Han, C. Zhao, S. Wang, Z. Pan, Z. Jiang and X. Tang, Multifunctional TiO_2/C nanosheets derived from 3D metal–organic frameworks for mild-temperature-photothermal-sonodynamic-chemodynamic therapy under photoacoustic image guidance, *J. Colloid Interface Sci.*, 2022, **621**, 360–373.
12 Z. Alakayleh, Sulfuric acid-activated carbon from guava leaves for paracetamol adsorption, *Results Eng.*, 2025, **25**, 103685.
13 S. Abbas, *et al.*, Cutting-edge metal-organic frameworks: revolutionizing the adsorptive removal of pharmaceutical contaminants from water, *Rev. Inorg. Chem.*, 2025, DOI: **10.1515/revic-2024-0119**.
14 M. Lammert, C. Glißmann and N. Stock, Tuning the stability of bimetallic Ce(IV)/Zr(IV)-based MOFs with UiO-66 and MOF-808 structures, *Dalton Trans.*, 2017, **46**(8), 2425–2429.
15 M. Y. Masoomi, A. Morsali, A. Dhakshinamoorthy and H. Garcia, Mixed-Metal MOFs: Unique Opportunities in Metal–Organic Framework (MOF) Functionality and Design, *Angew. Chem.*, 2019, **131**(43), 15330–15347, DOI: **10.1002/ange.201902229**.
16 B. Mohan, Priyanka, G. Singh, A. Chauhan, A. J. L. Pombeiro and P. Ren, Metal-organic frameworks (MOFs) based luminescent and electrochemical sensors for food contaminant detection, *J. Hazard. Mater.*, 2023, **453**, 131324, DOI: **10.1016/j.jhazmat.2023.131324**.
17 K. F. Kayani, O. B. A. Shatery, S. J. Mohammed, H. R. Ahmed, R. F. Hamarawf and M. S. Mustafa, Synthesis and applications of luminescent metal organic frameworks (MOFs) for sensing dipicolinic acid in biological and water samples: a review, *Nanoscale Adv.*, 2025, **7**(1), 13–41, DOI: **10.1039/D4NA00652F**.
18 K. F. Kayani, *et al.*, Ratiometric Lanthanide Metal-Organic Frameworks (MOFs) for Smartphone-Assisted Visual Detection of Food Contaminants and Water: A Review, *ChemistrySelect*, 2023, **8**(47), e202303472, DOI: **10.1002/slct.202303472**.
19 O. B. A. Shatery, K. F. Kayani, M. S. Mustafa and S. J. Mohammed, Rational design for enhancing sensitivity and robustness of a probe *via* encapsulation of carbon dots into a zeolitic imidazolate framework-8 for quantification of tetracycline in milk with greenness evaluation, *Res. Chem. Intermed.*, 2024, **50**, 2291–2306, DOI: **10.1007/s11164-024-05271-z**.
20 K. F. Kayani and K. M. Omer, A red luminescent europium metal organic framework (Eu-MOF) integrated with a paper strip using smartphone visual detection for determination of folic acid in pharmaceutical formulations, *New J. Chem.*, 2022, **46**(17), 8152–8161, DOI: **10.1039/d2nj00601d**.
21 Y. Qiao, *et al.*, Efficient removal of organic pollution *via* photocatalytic degradation over a TiO_2@HKUST-1 yolk-shell nanoreactor, *J. Mol. Liq.*, 2023, **385**, 122383.
22 K. Yuan, *et al.*, Bimetal–organic frameworks for functionality optimization: MnFe-MOF-74 as a stable and efficient catalyst for the epoxidation of alkenes with H_2O_2, *Nanoscale*, 2018, **10**(4), 1591–1597.
23 N. Raza, T. Kumar, V. Singh and K.-H. Kim, Recent advances in bimetallic metal-organic framework as a potential candidate for supercapacitor electrode material, *Coord. Chem. Rev.*, 2021, **430**, 213660.
24 W. S. Abo El-Yazeed, Y. G. Abou El-Reash, L. A. Elatwy and A. I. Ahmed, Novel bimetallic Ag-Fe MOF for exceptional Cd and Cu removal and 3,4-dihydropyrimidinone synthesis, *J. Taiwan Inst. Chem. Eng.*, 2020, **114**, 199–210, DOI: **10.1016/j.jtice.2020.09.028**.
25 K. F. Kayani, Nanozyme based on bimetallic metal–organic frameworks and their applications: a review, *Microchem. J.*, 2025, **208**, 112363, DOI: **10.1016/j.microc.2024.112363**.
26 S. Sanati, *et al.*, Metal–organic framework derived bimetallic materials for electrochemical energy storage, *Angew. Chem., Int. Ed.*, 2021, **60**(20), 11048–11067.
27 A. Kumari, S. Kaushal and P. P. Singh, Bimetallic metal organic frameworks heterogeneous catalysts: design, construction, and applications, *Mater. Today Energy*, 2021, **20**, 100667.
28 L. Martín-Pozo, B. de Alarcón-Gómez, R. Rodríguez-Gómez, M. T. García-Córcoles, M. Çipa and A. Zafra-Gómez, Analytical methods for the determination of emerging contaminants in sewage sludge samples. A review, *Talanta*, 2019, **192**, 508–533.
29 I. A. Saleh, N. Zouari and M. A. Al-Ghouti, Removal of pesticides from water and wastewater: chemical, physical and biological treatment approaches, *Environ. Technol. Innovation*, 2020, **19**, 101026.
30 N. H. Arihilam and E. C. Arihilam, Impact and control of anthropogenic pollution on the ecosystem-a review, *J. Biosci. Biotechnol. Discov.*, 2019, **4**(3), 54–59.
31 M. Ansari, M. H. Ehrampoush, M. Farzadkia and E. Ahmadi, Dynamic assessment of economic and environmental performance index and generation, composition, environmental and human health risks of

hospital solid waste in developing countries; a state of the art of review, *Environ. Int.*, 2019, **132**, 105073.
32 G. J. Nohynek, E. Antignac, T. Re and H. Toutain, Safety assessment of personal care products/cosmetics and their ingredients, *Toxicol. Appl. Pharmacol.*, 2010, **243**(2), 239–259.
33 W. Boedeker, M. Watts, P. Clausing and E. Marquez, The global distribution of acute unintentional pesticide poisoning: estimations based on a systematic review, *BMC Public Health*, 2020, **20**, 1–19.
34 E. Vulliet, C. Cren-Olivé and M.-F. Grenier-Loustalot, Occurrence of pharmaceuticals and hormones in drinking water treated from surface waters, *Environ. Chem. Lett.*, 2011, **9**(1), 103–114.
35 E. D. Nelson, H. Do, R. S. Lewis and S. A. Carr, Diurnal variability of pharmaceutical, personal care product, estrogen and alkylphenol concentrations in effluent from a tertiary wastewater treatment facility, *Environ. Sci. Technol.*, 2011, **45**(4), 1228–1234.
36 E. Y. Klein, *et al.*, Global increase and geographic convergence in antibiotic consumption between 2000 and 2015, *Proc. Natl. Acad. Sci. U. S. A.*, 2018, **115**(15), E3463–E3470.
37 A. Dunlop, *et al.*, Challenges in maintaining treatment services for people who use drugs during the COVID-19 pandemic, *Harm Reduct. J.*, 2020, **17**(1), 26.
38 A. C. Alder, *et al.*, *Occurrence and Fate of Fluoroquinolone, Macrolide, and Sulfonamide Antibiotics during Wastewater Treatment and in Ambient Waters in Switzerland*, ACS Publications, 2001.
39 B. Halling-Sørensen, Inhibition of aerobic growth and nitrification of bacteria in sewage sludge by antibacterial agents, *Arch. Environ. Contam. Toxicol.*, 2001, **40**, 451–460.
40 S. Chauhan, T. Shafi, B. K. Dubey and S. Chowdhury, Biochar-mediated removal of pharmaceutical compounds from aqueous matrices *via* adsorption, *Waste Disposal Sustainable Energy*, 2023, **5**(1), 37–62.
41 R. Natarajan, *et al.*, Understanding the factors affecting adsorption of pharmaceuticals on different adsorbents-a critical literature update, *Chemosphere*, 2022, **287**, 131958.
42 G. D. Alkimin, *et al.*, Evaluation of pharmaceutical toxic effects of non-standard endpoints on the macrophyte species *Lemna minor* and *Lemna gibba*, *Sci. Total Environ.*, 2019, **657**, 926–937.
43 S. L. Klosterhaus, R. Grace, M. C. Hamilton and D. Yee, Method validation and reconnaissance of pharmaceuticals, personal care products, and alkylphenols in surface waters, sediments, and mussels in an urban estuary, *Environ. Int.*, 2013, **54**, 92–99.
44 M. Patel, R. Kumar, K. Kishor, T. Mlsna, C. U. Pittman Jr and D. Mohan, Pharmaceuticals of emerging concern in aquatic systems: chemistry, occurrence, effects, and removal methods, *Chem. Rev.*, 2019, **119**(6), 3510–3673.
45 V. Vinayagam, *et al.*, Sustainable adsorbents for the removal of pharmaceuticals from wastewater: a review, *Chemosphere*, 2022, **300**, 134597, DOI: **10.1016/j.chemosphere.2022.134597**.
46 J. M. Brausch, K. A. Connors, B. W. Brooks and G. M. Rand, Human pharmaceuticals in the aquatic environment: a review of recent toxicological studies and considerations for toxicity testing, *Rev. Environ. Contam. Toxicol.*, 2012, **218**, 1–99.
47 S. Klatte, H.-C. Schaefer and M. Hempel, Pharmaceuticals in the environment – a short review on options to minimize the exposure of humans, animals and ecosystems, *Sustainable Chem. Pharm.*, 2017, **5**, 61–66, DOI: **10.1016/j.scp.2016.07.001**.
48 J. Hu, Y. Liu, J. Liu, C. Gu and D. Wu, High CO_2 adsorption capacities in UiO type MOFs comprising heterocyclic ligand, *Microporous Mesoporous Mater.*, 2018, **256**, 25–31.
49 S. Xiang, W. Zhou, J. M. Gallegos, Y. Liu and B. Chen, Exceptionally high acetylene uptake in a microporous metal–organic framework with open metal sites, *J. Am. Chem. Soc.*, 2009, **131**(34), 12415–12419.
50 W. Xiang, Y. Liao, J. Cui, Y. Fang, B. Jiao and X. Su, Room-temperature synthesis of Fe/Cu-BTC for effective removal of tetracycline antibiotic from aquatic environments, *Inorg. Chem. Commun.*, 2024, **167**, 112728, DOI: **10.1016/j.inoche.2024.112728**.
51 Y. Zhou, *et al.*, Bimetallic metal–organic frameworks and MOF-derived composites: recent progress on electro-and photoelectrocatalytic applications, *Coord. Chem. Rev.*, 2022, **451**, 214264.
52 K. R. Chithra, S. M. Rao, M. V Varsha and G. Nageswaran, Bimetallic Metal-Organic Frameworks (BMOF) and BMOF-Incorporated Membranes for Energy and Environmental Applications, *ChemPlusChem*, 2023, **88**(3), e202200420.
53 M. Fan, *et al.*, Synthesis and peroxide activation mechanism of bimetallic MOF for water contaminant degradation: a review, *Molecules*, 2023, **28**(8), 3622.
54 M. Ahmed, Recent advancement in bimetallic metal organic frameworks (M′ MOFs): synthetic challenges and applications, *Inorg. Chem. Front.*, 2022, **9**(12), 3003–3033.
55 F. Zheng, T. Lin, K. Wang, Y. Wang and G. Li, Recent advances in bimetallic metal-organic frameworks and their derivatives for thermal catalysis, *Nano Res.*, 2023, **16**(12), 12919–12935.
56 J.-K. Sun and Q. Xu, Functional materials derived from open framework templates/precursors: synthesis and applications, *Energy Environ. Sci.*, 2014, **7**(7), 2071–2100.
57 L. Chen, H.-F. Wang, C. Li and Q. Xu, Bimetallic metal–organic frameworks and their derivatives, *Chem. Sci.*, 2020, **11**(21), 5369–5403.
58 Y. Jiao, G. Chen, D. Chen, J. Pei and Y. Hu, Bimetal–organic framework assisted polymerization of pyrrole involving air oxidant to prepare composite electrodes for portable energy storage, *J. Mater. Chem. A*, 2017, **5**(45), 23744–23752.
59 K. F. Kayani, Bimetallic metal–organic frameworks (BMOFs) for dye removal: a review, *RSC Adv.*, 2024, **14**(43), 31777–31796, DOI: **10.1039/D4RA06626J**.
60 K. F. Kayani, Tetracycline in the environment: toxicity, uses, occurrence, detection, and removal by covalent organic frameworks – recent advances and challenges, *Sep. Purif.*

Technol., 2025, **364**, 132418, DOI: 10.1016/j.seppur.2025.132418.

61 C. Chen, D. Chen, S. Xie, H. Quan, X. Luo and L. Guo, Adsorption behaviors of organic micropollutants on zirconium metal–organic framework UiO-66: analysis of surface interactions, *ACS Appl. Mater. Interfaces*, 2017, **9**(46), 41043–41054.

62 R. Daghrir and P. Drogui, Tetracycline antibiotics in the environment: a review, *Environ. Chem. Lett.*, 2013, **11**, 209–227.

63 L. Jia, *et al.*, A stick-like intelligent multicolor nano-sensor for the detection of tetracycline: the integration of nano-clay and carbon dots, *J. Hazard. Mater.*, 2021, **413**, 125296, DOI: 10.1016/j.jhazmat.2021.125296.

64 L. Li, *et al.*, Red fluorescent carbon dots for tetracycline antibiotics and pH discrimination from aggregation-induced emission mechanism, *Sens. Actuators, B*, 2021, **332**, 129513, DOI: 10.1016/j.snb.2021.129513.

65 Y. Yan, J. H. Liu, R. S. Li, Y. F. Li, C. Z. Huang and S. J. Zhen, Carbon dots synthesized at room temperature for detection of tetracycline hydrochloride, *Anal. Chim. Acta*, 2019, **1063**, 144–151, DOI: 10.1016/j.aca.2019.02.047.

66 X. Chen, X. Liu, L. Zhu, X. Tao and X. Wang, One-step fabrication of novel MIL-53(Fe,Al) for synergistic adsorption-photocatalytic degradation of tetracycline, *Chemosphere*, 2022, **291**, 133032.

67 S. Xia, J. Sun and W. Sun, Bimetallic metal-organic gel for effective removal of chlortetracycline hydrochloride from aqueous solution: adsorption isotherm, kinetic and mechanism studies, *Colloids Surf., A*, 2022, **649**, 129403.

68 Z. Zhang, *et al.*, Tailored design of hierarchically porous metal/N-codoped carbon from soft-templated bimetallic ZIFs for the high-efficiency adsorption of tetracycline hydrochloride, *Sep. Purif. Technol.*, 2024, **333**, 125898.

69 R. Zhang, *et al.*, Critical trigger of self-assembled bimetallic Fe/Mn-MOF with SnS2 heterojunctions by persulfate activation for efficient tetracyclines photodegradation, *Environ. Res.*, 2024, **263**, 120060.

70 A. Liu, J. Liu, S. He, J. Zhang and W. Shao, Bimetallic MOFs loaded cellulose as an environment friendly bioadsorbent for highly efficient tetracycline removal, *Int. J. Biol. Macromol.*, 2023, **225**, 40–50.

71 W. Gu, Q. Li, H. Zhu and L. Zou, Facile interface engineering of hierarchical flower spherical-like Bi-metal–organic framework microsphere/Bi_2MoO_6 heterostructure for high-performance visible-light photocatalytic tetracycline hydrochloride degradation, *J. Colloid Interface Sci.*, 2022, **606**, 1998–2010, DOI: 10.1016/j.jcis.2021.10.004.

72 Y. Wu, *et al.*, 2D/2D FeNi-layered double hydroxide/bimetal-MOFs nanosheets for enhanced photo-Fenton degradation of antibiotics: performance and synergetic degradation mechanism, *Chemosphere*, 2022, **287**, 132061.

73 B. Liu, *et al.*, Carboxymethyl chitosan modification of cobalt-zinc bimetallic MOF for tetracycline hydrochloride removal: exploration of the enhancement mechanism of the process, *Int. J. Biol. Macromol.*, 2024, **274**, 133385, DOI: 10.1016/j.ijbiomac.2024.133385.

74 Y. Cao, *et al.*, Construction of Sn-Bi-MOF/Ti_3C_2 Schottky junction for photocatalysis of tetracycline: performance and degradation mechanism, *Appl. Surf. Sci.*, 2023, **609**, 155191, DOI: 10.1016/j.apsusc.2022.155191.

75 J. Wu, X. Fang, H. Dong, L. Lian, N. Ma and W. Dai, Bimetallic silver/bismuth-MOFs derived strategy for Ag/AgCl/BiOCl composite with extraordinary visible light-driven photocatalytic activity towards tetracycline, *J. Alloys Compd.*, 2021, **877**, 160262.

76 R. Zhang, K. Jia, Z. Xue, Z. Hu and N. Yuan, Modulation of CdS nanoparticles decorated bimetallic Fe/Mn-MOFs Z-scheme heterojunctions for enhancing photocatalytic degradation of tetracycline, *J. Alloys Compd.*, 2024, **992**, 174462, DOI: 10.1016/j.jallcom.2024.174462.

77 Y. Zhu, X. Nie and X. Liu, Preparation of Fe/Co bimetallic MOF photofenton catalysts and their performance in degrading tetracycline hydrochloride pollutants efficiently under visible light, *J. Alloys Compd.*, 2025, **1010**, 176967, DOI: 10.1016/j.jallcom.2024.176967.

78 L. Gao, D. Han, Z. Wang and F. Gu, Metal-organic framework MIL-68(In)-NH_2-derived carbon-covered cobalt-doped bi-crystalline In_2O_3 tubular structures for efficient photocatalytic degradation of tetracycline hydrochloride, *Colloids Surf., A*, 2023, **661**, 130931.

79 Y. Zhang, *et al.*, Superoxide radical mediated persulfate activation by nitrogen doped bimetallic MOF (FeCo/N-MOF) for efficient tetracycline degradation, *Sep. Purif. Technol.*, 2022, **282**, 120124.

80 H. Zhu, *et al.*, Synthesis of bimetallic NbCo-piperazine catalyst and study on its advanced redox treatment of pharmaceuticals and personal care products by activation of permonosulfate, *Sep. Purif. Technol.*, 2022, **285**, 120345.

81 Y.-C. Jiang, *et al.*, *In situ* growth of bimetallic FeCo-MOF on magnetic biochar for enhanced clearance of tetracycline and fruit preservation, *Chem. Eng. J.*, 2023, **451**, 138804.

82 T. R. Katugampalage, *et al.*, Bimetallic Fe: Co metal–organic framework (MOF) with unsaturated metal sites for efficient Fenton-like catalytic degradation of oxytetracycline (OTC) antibiotics, *Chem. Eng. J.*, 2024, **479**, 147592.

83 S. Zhang, Z. Shao and D. Wu, Preparation and performance of FeCo bimetallic organic frameworks with super adsorption and excellent peroxymonosulfate activation for tetracycline removal, *Arabian J. Chem.*, 2024, **17**(1), 105483.

84 F. M. Jais, S. Ibrahim, C. Y. Chee and Z. Ismail, Solvothermal growth of the bimetal organic framework (NiFe-MOF) on sugarcane bagasse hydrochar for the removal of dye and antibiotic, *J. Environ. Chem. Eng.*, 2021, **9**(6), 106367.

85 Q. Zhang, *et al.*, A novel Fe-based bi-MOFs material for photocatalytic degradation of tetracycline: performance, mechanism and toxicity assessment, *J. Water Process Eng.*, 2021, **44**, 102364, DOI: 10.1016/j.jwpe.2021.102364.

86 H. Zhao, X. Shang, Y. Liu, D. Wu and M. Lv, Highly efficient peroxymonosulfate activation by FeCo bimetallic modified metal-organic frameworks-derived polyhedron with enriched oxygen vacancy for tetracycline degradation, *J.*

Water Process Eng., 2024, **58**, 104903, DOI: 10.1016/j.jwpe.2024.104903.

87 S. Kaushal, P. P. Singh and N. Kaur, Metal organic framework-derived Zr/Cu bimetallic photocatalyst for the degradation of tetracycline and organic dyes, *Environ. Nanotechnol., Monit. Manage.*, 2022, **18**, 100727.

88 X. Zhao, *et al.*, Enhancing photocatalytic performance of Ni-Ti bimetallic metal-organic frameworks for tetracycline degradation under visible light irradiation, *Mater. Today Commun.*, 2024, **39**, 109015, DOI: 10.1016/j.mtcomm.2024.109015.

89 Q. Wang, *et al.*, Magnetically separable Zn_2FeO_x@CN microcubes derived from metal-organic frameworks for efficient tetracycline removal, *Surf. Interfaces*, 2025, **56**, 105698, DOI: 10.1016/j.surfin.2024.105698.

90 Q. Mo, H. Zheng and G. Sheng, A heterogeneously activated peroxymonosulfate with a Co and Cu codoped bimetallic metal-organic framework efficiently degrades tetracycline in water, *Mol. Catal.*, 2024, **553**, 113817, DOI: 10.1016/j.mcat.2023.113817.

91 T. T. A. Le, B. H. Dang, T. Q. C. Nguyen, D. P. Nguyen and G. H. Dang, Highly efficient removal of tetracycline and methyl violet 2B from aqueous solution using the bimetallic FeZn-ZIFs catalyst, *Green Process. Synth.*, 2023, **12**(1), 20230122.

92 F. Wei, *et al.*, Preparation of bimetallic metal–organic frameworks for adsorbing doxycycline hydrochloride from wastewater, *Appl. Organomet. Chem.*, 2023, **37**(9), e7212.

93 Z. Wang, C. Wu, Z. Zhang, Y. Chen, W. Deng and W. Chen, Bimetallic Fe/Co-MOFs for tetracycline elimination, *J. Mater. Sci.*, 2021, **56**(28), 15684–15697, DOI: 10.1007/s10853-021-06280-8.

94 Y. Zhao, *et al.*, Bimetal doped Cu–Fe-ZIF-8/gC_3N_4 nanocomposites for the adsorption of tetracycline hydrochloride from water, *RSC Adv.*, 2024, **14**(7), 4861–4870.

95 C. V. Flores, *et al.*, Room-temperature synthesis of bimetallic ZnCu-MOF-74 as an adsorbent for tetracycline removal from an aqueous solution, *Dalton Trans.*, 2024, **53**(47), 18917–18922, DOI: 10.1039/D4DT01607F.

96 Y. Jin, X. Mi, J. Qian, N. Ma and W. Dai, CdS Nanoparticles Supported on a Dual Metal–Organic Framework as a Catalyst for the Photodegradation of Tetracycline, *ACS Appl. Nano Mater.*, 2024, **7**(3), 3154–3167.

97 H. Laddha, P. Sharma, N. B. Jadhav, M. Z. Abedeen and R. Gupta, Batch Experimental Studies and Statistical Modeling for the Effective Removal of Tetracycline from Wastewater Using Bimetallic Zn–Cu-Metal–Organic Framework@Hydrogel Composite Beads, *Langmuir*, 2023, **39**(49), 17756–17769.

98 K.-P. Cui, *et al.*, Degradation of tetracycline hydrochloride by Cu-doped MIL-101(Fe) loaded diatomite heterogeneous Fenton catalyst, *Nanomaterials*, 2022, **12**(5), 811.

99 Q. Liu, H. Zhang, K. Zhang, J. Li, J. Cui and T. Shi, Iron–Cobalt Bimetallic Metal–Organic Framework-Derived Carbon Materials Activate PMS to Degrade Tetracycline Hydrochloride in Water, *Water*, 2024, **16**(20), 2997.

100 S. K. Mondal, A. K. Saha and A. Sinha, Removal of ciprofloxacin using modified advanced oxidation processes: kinetics, pathways and process optimization, *J. Cleaner Prod.*, 2018, **171**, 1203–1214, DOI: 10.1016/j.jclepro.2017.10.091.

101 Y. Wang, Q. Nie, B. Huang, H. Cheng, L. Wang and Q. He, Removal of ciprofloxacin as an emerging pollutant: a novel application for bauxite residue reuse, *J. Cleaner Prod.*, 2020, **253**, 120049, DOI: 10.1016/j.jclepro.2020.120049.

102 J. Li, *et al.*, Study of ciprofloxacin removal by biochar obtained from used tea leaves, *J. Environ. Sci.*, 2018, **73**, 20–30, DOI: 10.1016/j.jes.2017.12.024.

103 K. Li, *et al.*, MOF-on-MOF-derived FeZr bimetal oxides supported on hierarchically porous carbonized wood to promote photo-Fenton degradation of ciprofloxacin, *J. Water Process Eng.*, 2024, **63**, 105442.

104 Y. Zhang, W. Zhao, X. Zhang and S. Wang, Highly efficient targeted adsorption and catalytic degradation of ciprofloxacin by a novel molecularly imprinted bimetallic MOFs catalyst for persulfate activation, *Chemosphere*, 2024, **357**, 141894.

105 Q. Wu, M. S. Siddique, Y. Guo, M. Wu, Y. Yang and H. Yang, Low-crystalline bimetallic metal-organic frameworks as an excellent platform for photo-Fenton degradation of organic contaminants: intensified synergism between hetero-metal nodes, *Appl. Catal., B*, 2021, **286**, 119950, DOI: 10.1016/j.apcatb.2021.119950.

106 M.-M. Chen, H.-Y. Niu, C.-G. Niu, H. Guo, S. Liang and Y.-Y. Yang, Metal-organic framework-derived CuCo/carbon as an efficient magnetic heterogeneous catalyst for persulfate activation and ciprofloxacin degradation, *J. Hazard. Mater.*, 2022, **424**, 127196.

107 J. Yang, *et al.*, Synthesis of cake-like Ti-Bi bimetallic MOFs-derived OV-rich A-TiO_2/β-Bi_2O_3 heterojunctions for photodegradation of ciprofloxacin, *J. Alloys Compd.*, 2023, **957**, 170277.

108 H. Alamgholiloo, E. Asgari, S. Nazari, A. Sheikhmohammadi, N. N. Pesyan and B. Hashemzadeh, Architecture of bimetallic-MOF/silicate derived Co/NC@mSiO_2 as peroxymonosulfate activator for highly efficient ciprofloxacin degradation, *Sep. Purif. Technol.*, 2022, **300**, 121911.

109 Q. Luo, *et al.*, Selective and efficient removal of ciprofloxacin from water by bimetallic MOF beads: mechanism quantitative analysis and dynamic adsorption, *Sep. Purif. Technol.*, 2024, **332**, 125832.

110 S. Parsaei, M. Rashid, A. Ghoorchian, K. Dashtian and D. Mowla, Bi-metal-organic framework-derived S-scheme InP/CuO-C heterostructure for robust photocatalytic degradation of ciprofloxacin in a microfluidic photoreactor, *Chem. Eng. J.*, 2023, **475**, 146448.

111 S. P. Tripathy, S. Subudhi, A. Ray, P. Behera, A. Bhaumik and K. Parida, Mixed-valence bimetallic Ce/Zr MOF-based nanoarchitecture: a visible-light-active photocatalyst for ciprofloxacin degradation and hydrogen evolution, *Langmuir*, 2022, **38**(5), 1766–1780.

112 A. Chatterjee, A. K. Jana and J. K. Basu, A binary MOF of iron and copper for treating ciprofloxacin-contaminated waste water by an integrated technique of adsorption and photocatalytic degradation, *New J. Chem.*, 2021, **45**(37), 17196–17210.

113 X. Li, *et al.*, Bimetallic Fe_xMn_y catalysts derived from metal organic frameworks for efficient photocatalytic removal of quinolones without oxidant, *Environ. Sci.: Nano*, 2021, **8**(9), 2595–2606.

114 Y. Shao, Y. Wang, Y. Yuan and Y. Xie, A systematic review on antibiotics misuse in livestock and aquaculture and regulation implications in China, *Sci. Total Environ.*, 2021, **798**, 149205.

115 Y. Chu, C. Zhang, R. Wang, X. Chen, N. Ren and S.-H. Ho, Biotransformation of sulfamethoxazole by microalgae: removal efficiency, pathways, and mechanisms, *Water Res.*, 2022, **221**, 118834, DOI: **10.1016/j.watres.2022.118834**.

116 P. Zhang, *et al.*, Embedded iron and nitrogen co-doped carbon quantum dots within g-C_3N_4 as an exceptional PMS photocatalytic activator for sulfamethoxazole degradation: the key role of FeN bridge, *Sep. Purif. Technol.*, 2024, **342**, 126975, DOI: **10.1016/j.seppur.2024.126975**.

117 J. Tang and J. Wang, Iron-copper bimetallic metal-organic frameworks for efficient Fenton-like degradation of sulfamethoxazole under mild conditions, *Chemosphere*, 2020, **241**, 125002.

118 D. Wu, *et al.*, Two-dimensional manganese-iron bimetallic MOF-74 for electro-Fenton degradation of sulfamethoxazole, *Chemosphere*, 2023, **327**, 138514.

119 G. Zhou, Y. Liu, R. Zhou, L. Zhang and Y. Fu, Bimetallic metal-organic framework as a high-performance peracetic acid activator for sulfamethoxazole degradation, *Chemosphere*, 2024, **349**, 140958.

120 D.-H. Xie, P.-C. Guo, K.-Q. Zhong and G.-P. Sheng, Highly dispersed Co/Fe bimetal in carbonaceous cages as heterogeneous Fenton nanocatalysts for enhanced sulfamethoxazole degradation, *Appl. Catal., B*, 2022, **319**, 121923.

121 Y. Guo, C. Zhou, X. Lv, S. Du and M. Sui, Sustainable Co(III)/Co(II) cycles triggered by Co-Zn bimetallic MOF encapsulating Fe nanoparticles for high-efficiency peracetic acid activation to degrade sulfamethoxazole: enhanced performance and synergistic mechanism, *Sep. Purif. Technol.*, 2025, **354**, 128729.

122 X. Peng, J. Li, S. Liu, P. Zeng and M. Shan, Bimetallic FeCo-MOF as peroxymonosulfate activator for efficient degradation of sulfamethoxazole: performance and mechanism, *Mol. Catal.*, 2025, **572**, 114751.

123 X. Yuan, S. Li, J. Hu, M. Yu, Y. Li and Z. Wang, Experiments and numerical simulation on the degradation processes of carbamazepine and triclosan in surface water: a case study for the Shahe Stream, South China, *Sci. Total Environ.*, 2019, **655**, 1125–1138, DOI: **10.1016/j.scitotenv.2018.11.290**.

124 O. Ganzenko, P. Sistat, C. Trellu, V. Bonniol, M. Rivallin and M. Cretin, Reactive electrochemical membrane for the elimination of carbamazepine in secondary effluent from wastewater treatment plant, *Chem. Eng. J.*, 2021, **419**, 129467.

125 C. Yu, S. Lan, S. Cheng, L. Zeng and M. Zhu, Ba substituted $SrTiO_3$ induced lattice deformation for enhanced piezocatalytic removal of carbamazepine from water, *J. Hazard. Mater.*, 2022, **424**, 127440, DOI: **10.1016/j.jhazmat.2021.127440**.

126 Y. Zheng, X. Du, G. Song, J. Gu, J. Guo and M. Zhou, Degradation of carbamazepine over MOFs derived FeMn@C bimetallic heterogeneous electro-Fenton catalyst, *Chemosphere*, 2023, **312**, 137353.

127 D. Roy, S. S. Chowdhury and S. De, Unveiling the mechanism of visible light-assisted peroxymonosulfate activation and carbamazepine degradation using NH_2-MIL-125(Ti)@MIL-53(Fe/Co) heterojunction photocatalyst, *Environ. Sci.: Nano*, 2024, **11**(1), 389–405.

128 V.-A. Thai, T.-B. Nguyen, C.-W. Chen, X.-T. Bui, R. Doong and C.-D. Dong, Synergistic bimetallic MOF-integrated MXene nanosheets for enhanced catalytic degradation of carbamazepine and hydrogen production: a dual-function approach for water remediation and energy applications, *Environ. Sci.: Nano*, 2024, **11**(9), 3871–3886.

129 Q.-Q. Huang, Y.-M. Wang, X. Fu, X.-L. Hu, J.-W. Wang and Z.-M. Su, Efficient bimetallic metal–organic framework derived magnetic Co/N-PC-800 nanoreactor for peroxymonosulfate activation and carbamazepine degradation, *Environ. Sci.: Nano*, 2025, **12**, 1609–1625.

130 G. Fan, *et al.*, Rapid synthesis of Ag/AgCl@ZIF-8 as a highly efficient photocatalyst for degradation of acetaminophen under visible light, *Chem. Eng. J.*, 2018, **351**, 782–790.

131 H. Nourmoradi, K. F. Moghadam, A. Jafari and B. Kamarehie, Removal of acetaminophen and ibuprofen from aqueous solutions by activated carbon derived from *Quercus brantii* (oak) acorn as a low-cost biosorbent, *J. Environ. Chem. Eng.*, 2018, **6**(6), 6807–6815.

132 H. Yang, G.-R. Choi, Y. Jae Jeong, I. S. Cho, S.-J. Park and C.-G. Lee, Enhancing acetaminophen removal through persulfate activation with $ZnCl_2$-SPI biochar: a study on reactive oxygen species contribution according to acetaminophen concentration, *Chem. Eng. J.*, 2024, **496**, 154065, DOI: **10.1016/j.cej.2024.154065**.

133 S. H. Alrefaee, *et al.*, Removal of acetaminophen from wastewater using a novel bimetallic La/Th metal-organic framework: kinetics, thermodynamics, isotherms, and optimization through Box-Behnken design, *Process Saf. Environ. Prot.*, 2024, **189**, 1134–1150.

134 D. Pattappan, *et al.*, Visible light photocatalytic activity of a FeCo metal-organic framework for degradation of acetaminophen and 2,4-dichlorophenoxyacetic acid and a nematode-based ecological assessment, *Chem. Eng. J.*, 2023, **464**, 142676.

135 X. Li, *et al.*, Recognizing the relevance of non-radical peroxymonosulfate activation by co-doped Fe metal-organic framework for the high-efficient degradation of acetaminophen: role of singlet oxygen and the

enhancement of redox cycle, *Chem. Eng. J.*, 2024, **499**, 156081.

136 J. Lin, *et al.*, Removal of chloramphenicol antibiotics in natural and engineered water systems: review of reaction mechanisms and product toxicity, *Sci. Total Environ.*, 2022, **850**, 158059, DOI: 10.1016/j.scitotenv.2022.158059.

137 O. Falyouna, *et al.*, Sustainable technologies for the removal of chloramphenicol from pharmaceutical industries effluent: a critical review, *J. Mol. Liq.*, 2022, **368**, 120726, DOI: 10.1016/j.molliq.2022.120726.

138 J. Li, *et al.*, Insights into the removal of chloramphenicol by electrochemical reduction on Pd/NiFe-MOF/foam-Ni electrode: performance and mechanism, *Appl. Catal., B*, 2023, **322**, 122076, DOI: 10.1016/j.apcatb.2022.122076.

139 C. Xue, H. Wang, H. Liu, D. Liu and W. Huang, Ce/Fe bimetallic MOF derivatives *in situ* modified bulk carbon aerogel composite cathode for efficient heterogeneous electro-Fenton degradation of chloramphenicol, *J. Cleaner Prod.*, 2024, **448**, 141550.

140 Y. Lei, *et al.*, Nitrogen-doped bimetallic MOFs derivatives for efficient ionizing radiation catalytic degradation of chloramphenicol, *Sep. Purif. Technol.*, 2023, **326**, 124785.

141 H. Rashid Ahmed, K. F. Kayani, A. Mary Ealias and G. George, Biochar as an eco-friendly adsorbent for ibuprofen removal *via* adsorption: a review, *Inorg. Chem. Commun.*, 2024, **170**, 113397, DOI: 10.1016/j.inoche.2024.113397.

142 L. Zhang, *et al.*, Effects of constructed wetland design on ibuprofen removal – a mesocosm scale study, *Sci. Total Environ.*, 2017, **609**, 38–45, DOI: 10.1016/j.scitotenv.2017.07.130.

143 L. Sruthi, B. Janani and S. Sudheer Khan, Ibuprofen removal from aqueous solution *via* light-harvesting photocatalysis by nano-heterojunctions: a review, *Sep. Purif. Technol.*, 2021, **279**, 119709, DOI: 10.1016/j.seppur.2021.119709.

144 D. N. R. de Sousa, A. A. Mozeto, R. L. Carneiro and P. S. Fadini, Electrical conductivity and emerging contaminant as markers of surface freshwater contamination by wastewater, *Sci. Total Environ.*, 2014, **484**, 19–26.

145 X. Li, L. Wang, X. Zheng, X. Tu, A. Cai and J. Deng, Efficiently photocatalysis activation of peroxymonosulfate by bimetallic metal-organic frameworks Mn-MIL-53 (Fe) for ibuprofen degradation: synergistic efficiency, mechanism and degradation pathways, *Environ. Res.*, 2024, 119348.

146 V.-A. Thai, *et al.*, Enhancing ibuprofen degradation in aqueous solutions: the synergistic role of bimetallic MOFs (Mn/ZIF-67) and modified graphene oxide in peroxymonosulfate activation, *Sep. Purif. Technol.*, 2024, **334**, 126033.

147 Z. Hasan, N. A. Khan and S. H. Jhung, Adsorptive removal of diclofenac sodium from water with Zr-based metal–organic frameworks, *Chem. Eng. J.*, 2016, **284**, 1406–1413, DOI: 10.1016/j.cej.2015.08.087.

148 L. Wu, C. Du, J. He, Z. Yang and H. Li, Effective adsorption of diclofenac sodium from neutral aqueous solution by low-cost lignite activated cokes, *J. Hazard. Mater.*, 2020, **384**, 121284, DOI: 10.1016/j.jhazmat.2019.121284.

149 J. Wang, Y. Su, S.-W. Lv and L.-H. Sun, The efficient removal of diclofenac sodium and bromocresol green from aqueous solution by sea urchin-like Ni/Co-BTC bimetallic organic framework: adsorption isotherms, kinetics and mechanisms, *New J. Chem.*, 2022, **46**(38), 18374–18383.

150 X. He, L. Yang and C. Chang, Construction of Bi-Zr Bimetallic MOF for Adsorption and Photocatalytic Degradation Toward DCF, *Water, Air, Soil Pollut.*, 2024, **235**(7), 459.

151 L. Wang, C. Tang, P. Huang, X. Hu and Z. Sun, Efficient degradation of ceftazidime in heterogeneous electro-Fenton process with Fe/Cu bimetal MOF-derived nitrogen-doped cathode, *J. Alloys Compd.*, 2023, **945**, 169263.

152 M. Ghorbani, A. Saghafi, M. Pakseresht, A. Shams, M. Keshavarzi and S. Asghari, Crafting an innovative bimetallic MOF-on-MOF/TiO_2 composite for effective removal of imatinib anticancer agent through adsorption and photodegradation, *Sep. Purif. Technol.*, 2024, **336**, 126227.

153 L. R. Rad, H. Faramarzi, M. Anbia and M. Irani, Adsorption of doxorubicin and 5-Fluorouracil anticancer drugs from aqueous media using MIL-101-NH_2 (Co/Fe) bi-metal–organic framework, *Sep. Purif. Technol.*, 2024, **339**, 126597.

154 J. Hu, *et al.*, Synthesis of bimetal MOFs for rapid removal of doxorubicin in water by advanced oxidation method, *RSC Adv.*, 2022, **12**(55), 35666–35675.

155 A. K. Aldhalmi, *et al.*, A novel fabricate of iron and nickel-introduced bimetallic MOFs for quickly catalytic degradation *via* the peroxymonosulfate, antibacterial efficiency, and cytotoxicity assay, *Inorg. Chem. Commun.*, 2023, **153**, 110823.

156 L. Yu, Y. Zhao, S. Guo and J. Xue, Fe/Cu Bimetallic Nanoparticles Highly Dispersed in MOF-Derived N-Doped Porous Carbon as Stable Heterogeneous Fenton Catalysts for Enrofloxacin Degradation, *Catal. Lett.*, 2024, 1–15.

157 Y. Du, *et al.*, Constructing of Fe-Cu bimetallic MOFs derived electro-Fenton cathode for efficient norfloxacin removal, *J. Environ. Chem. Eng.*, 2024, **12**(2), 112324.

158 H. Wang, X. Zhang, Y. Wang, G. Quan, X. Han and J. Yan, Facile synthesis of magnetic nitrogen-doped porous carbon from bimetallic metal–organic frameworks for efficient norfloxacin removal, *Nanomaterials*, 2018, **8**(9), 664.

159 A. Anum, *et al.*, Synthesis of Bi-metallic-sulphides/MOF-5@graphene oxide nanocomposites for the removal of hazardous moxifloxacin, *Catalysts*, 2023, **13**(6), 984.

160 H. M. A. El Salam and E. M. El-Fawal, Optimized photocatalytic degradation of antibiotics with modified Co-MOF and NiCo-MOF catalysts, *Environ. Processes*, 2024, **11**(3), 40.

161 Z. Gordi and T. Ghanbari, Enhanced photodegradation of sertraline using a hybrid-metal–organic framework

composite photocatalyst: optimization and kinetic study, *React. Kinet., Mech. Catal.*, 2024, **137**(3), 1839–1859.

162 L. Zheng, *et al.*, Hierarchical Porous Bimetallic FeMn Metal–Organic Framework Gel for Efficient Activation of Peracetic Acid in Antibiotic Degradation, *ACS Environ. Au*, 2023, **4**(2), 56–68.

163 J. Lu, *et al.*, Enhancing bimetallic redox cycling by olsalazine-based MOF to achieve efficient removal of ofloxacin, *Sep. Purif. Technol.*, 2025, **355**, 129521.

164 Y. Zhou, L. Yu, Y. Gao, J. Wu and W. Dai, Effective capture of cefradines in water with a highly stable Zr (IV)-based bimetal–organic framework, *Ind. Eng. Chem. Res.*, 2019, **58**(41), 19202–19210.