

Review

Recent Progress in Antibiotic Degradation by Porphyrin-Based Metal–Organic Frameworks

Dimitrios Rafail Bitsos , Maria-Chrysanthi Kafentzi and Kalliopi Ladomenou * 

Hephaestus Laboratory, School of Chemistry, Faculty of Science, Democritus University of Thrace, Kavala University Campus, St. Lucas, 65404 Kavala, Greece

* Correspondence: kladomenou@chem.duth.gr

Abstract

The increasing presence of antibiotic residues in aquatic environments has emerged as a significant global environmental and public health concern. Conventional wastewater treatment technologies are often insufficient to completely remove these persistent contaminants, leading to the spread of antibiotic resistance and ecological toxicity. In recent years, metal–organic frameworks have attracted considerable attention as promising materials for water remediation due to their high surface area, tunable porosity, and structural versatility. Among them, porphyrin-based MOFs (Por-MOFs) represent an especially powerful class of photocatalysts owing to their excellent light-harvesting ability, efficient charge transfer properties, and capacity to generate reactive oxygen species under visible light. This review summarizes recent advances in the design and application of porphyrin-based MOFs for the degradation of antibiotic pollutants in water systems. Particular emphasis is placed on the structural design strategies of Por-MOFs, including ligand engineering, metal node selection, defect engineering, and the construction of heterostructures such as Z-scheme photocatalytic systems. The photocatalytic mechanisms responsible for antibiotic degradation, including singlet oxygen generation, photo-Fenton processes, and charge transfer pathways, are discussed in detail. Furthermore, representative studies on the removal of antibiotics such as ciprofloxacin, tetracycline, chloramphenicol, sulfathiazole, norfloxacin, and amoxicillin are analyzed to highlight the performance and limitations of these materials. Finally, current challenges and future perspectives for the development of next-generation porphyrin-based MOFs for sustainable environmental remediation are discussed, including stability in aqueous environments, large-scale synthesis, and integration into practical water treatment technologies.

Keywords: porphyrins; metal–organic frameworks; antibiotic degradation; photocatalysis; water remediation; environmental pollutants



Academic Editor: Francis Verpoort

Received: 11 June 2026

Revised: 6 July 2026

Accepted: 8 July 2026

Published: 11 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The widespread use of antibiotics in human [1] and veterinary medicine [2], aquaculture [3], and agriculture [4,5] has significantly improved the treatment and prevention of bacterial infections, contributing substantially to public health and food production. However, the extensive consumption of these compounds has also resulted in their continuous release into the environment. It is estimated that between 50% and 90% of administered antibiotics are excreted either unchanged or as active metabolites through urine and feces, ultimately entering natural ecosystems. Due to the limited removal efficiency of conventional wastewater treatment plants (WWTPs), substantial quantities of antibiotics are

discharged into rivers, lakes, groundwater, coastal waters, and even drinking water sources, resulting in chronic environmental exposure and increasing concerns regarding human health risk [6,7] (Figure 1).

The environmental persistence of antibiotics has emerged as a major global challenge. Their continuous accumulation in aquatic and terrestrial ecosystems can adversely affect microbial communities and non-target organisms while promoting the development and dissemination of antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs) [8–13]. The latter can be transferred among microorganisms through horizontal gene transfer, accelerating the spread of antimicrobial resistance and reducing the effectiveness of existing antibiotic therapies. In addition to domestic and agricultural sources, industrial discharges from pharmaceutical manufacturing facilities further contribute to environmental contamination. Recent projections suggest that antibiotic pollution may increase significantly in the coming years, emphasizing the urgent need for effective remediation strategies [14].

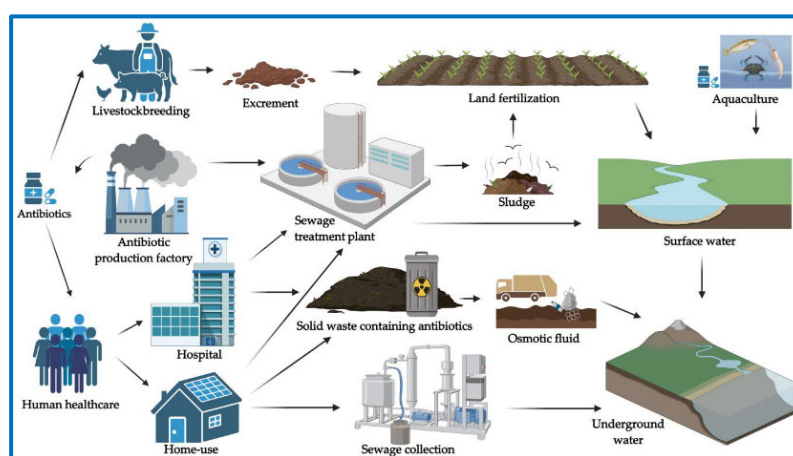


Figure 1. The main routes of antibiotic pollution in natural environments produced from ref [15].

Antibiotics encompass a diverse group of compounds, including β -lactams, macrolides, tetracyclines, quinolones, fluoroquinolones, and sulfonamides, each characterized by distinct physicochemical properties [6] and environmental behaviors [11] (Figure 2). The classification of antibiotics based on their characteristics (hydrophilicity and stability) and functional groups leads to a range of physicochemical behaviors within ecosystems [11]. Their persistence in natural environments depends largely on their molecular structure, hydrophilicity, stability, and susceptibility to biological or chemical degradation. While some compounds, such as penicillin and amoxicillin, undergo relatively rapid degradation, others, including ciprofloxacin, tetracycline, sulfadiazine, and various fluoroquinolones, exhibit remarkable environmental stability and can persist for extended periods. Consequently, these compounds are frequently detected in wastewater, surface waters, sediments, soils, and agricultural products.

A variety of treatment technologies have been investigated for the removal of antibiotics from contaminated waters, including membrane filtration [16], photocatalysis [17], biological treatment [18], coagulation [19], advanced oxidation processes [20], electrochemical treatment [21], and adsorption [22]. Although many of these approaches exhibit satisfactory removal efficiencies under controlled conditions, their practical implementation is often hindered by high operational costs, energy requirements, membrane fouling, incomplete degradation, the formation of toxic intermediates, secondary pollution, and limited reusability [23]. Therefore, the development of sustainable and efficient treatment

technologies capable of achieving complete antibiotic degradation remains a priority in environmental remediation research [14].

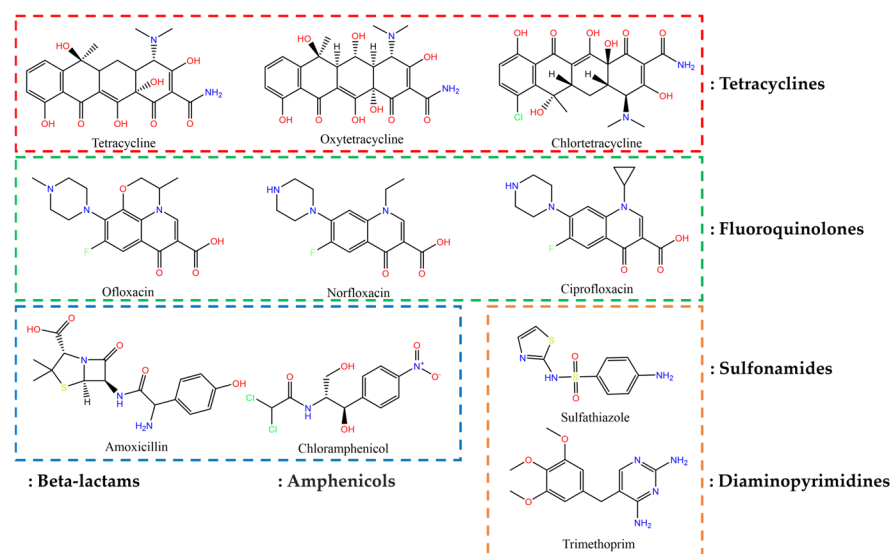


Figure 2. Chemical structure and classification of antibiotics.

Among the emerging treatment approaches, photocatalysis has attracted considerable attention as an environmentally benign and energy-efficient strategy for the degradation of persistent organic contaminants [24,25]. Unlike conventional treatment methods that primarily transfer pollutants from one phase to another, photocatalytic processes can mineralize contaminants through the generation of highly reactive oxidative species. Upon light irradiation, photocatalysts generate electron–hole pairs that subsequently produce reactive oxygen species (ROS), including hydroxyl radicals ($\bullet\text{OH}$), superoxide radicals ($\text{O}_2^{\bullet-}$), and singlet oxygen ($^1\text{O}_2$). These reactive species attack antibiotic molecules and promote their transformation into smaller and, ideally, less harmful products. Consequently, photocatalytic degradation has emerged as a promising strategy for addressing antibiotic contamination in aquatic environments.

A wide range of photocatalytic materials has been explored for antibiotic degradation, including metal oxides [26,27], bismuth-based semiconductors [28], graphitic carbon nitride ($\text{g-C}_3\text{N}_4$) [29], MXenes [30,31], covalent-organic frameworks (COFs) [17,32] and metal-organic frameworks (MOFs) [24,33]. However, many of these materials still exhibit several limitations, such as limited light absorption, wide band gaps, rapid recombination of photogenerated electron-hole pairs, poor chemical stability, low photocatalytic efficiencies, and potential toxicity, all of which hinder their wider application. Consequently, there is an urgent need to develop materials with enhanced stability, high crystallinity, and superior photocatalytic performance.

Among these materials, MOFs have attracted particular interest because they combine exceptionally high surface areas, tunable pore architectures, adjustable electronic structures, and versatile chemical functionalities within a single platform [34]. MOFs are crystalline porous materials constructed from metal ions or metal clusters interconnected by organic linkers. Their modular nature allows precise control over pore size, topology, surface chemistry [35], and catalytic properties, making them highly attractive for adsorption [36,37], sensing [38], catalysis, and environmental remediation applications [39].

Particularly promising among MOF-based photocatalysts are porphyrin-based metal-organic frameworks (Por-MOFs). Porphyrins are highly conjugated aromatic macrocycles characterized by intense absorption in the visible region, excellent photochemical stability, and remarkable light-harvesting capabilities [40]. Their unique electronic structure facili-

tates efficient charge separation and transfer while promoting the generation of reactive oxygen species under light irradiation [41]. Furthermore, porphyrins readily coordinate a wide variety of metal ions, enabling fine control over their optical, electronic, and catalytic properties through metalation and peripheral functionalization [42]. The incorporation of porphyrins into MOF architectures creates a highly synergistic platform in which the photophysical properties of porphyrins are combined with the structural advantages of MOFs. The resulting Por-MOFs benefit from enhanced visible-light absorption, efficient charge transport, large numbers of accessible active sites, and improved pollutant adsorption capabilities [43]. In many cases, the porous framework serves not only as a support for the photosensitizer but also as a means of preconcentrating antibiotic molecules near catalytic sites, thereby facilitating their subsequent degradation. This integration of adsorption, light harvesting, charge separation, and catalytic transformation within a single material has positioned Por-MOFs among the most promising photocatalysts for environmental remediation [43]. Beyond antibiotic degradation, porphyrin systems have demonstrated remarkable performance in a wide variety of applications [44], including hydrogen evolution [45,46], overall water splitting [47,48], carbon dioxide reduction [49,50], contaminant degradation [51,52], sensing [53], photodynamic therapy [54], and biomedical technologies [55]. In environmental applications, their ability to selectively generate reactive oxygen species under visible-light irradiation has proven particularly advantageous for the degradation of persistent organic pollutants.

Despite these significant advances, several challenges continue to limit the practical implementation of Por-MOFs in water treatment systems. Issues related to hydrolytic stability, photocorrosion, metal and ligand leaching, catalyst recovery and recyclability, large-scale synthesis, and long-term operation under realistic environmental conditions remain important obstacles [45]. At the same time, recent developments in framework engineering, heterojunction construction, defect modulation, and photocatalytic mechanism elucidation have substantially expanded the capabilities of these materials and opened new opportunities for their optimization [56].

Although numerous reviews have discussed the synthesis, properties, and broad environmental applications of porphyrin-based MOFs, a comprehensive and up-to-date evaluation specifically focused on antibiotic degradation remains lacking [43,45,57]. Most existing reviews address photocatalytic pollutant degradation in general or discuss Por-MOFs within broader materials categories without providing a dedicated analysis of antibiotic removal processes. The present review focuses on antibiotic degradation by Por-MOFs, highlighting degradation mechanisms, structure-performance relationships, catalyst stability and reusability, and recent advances in photocatalytic performance. Therefore, a critical assessment of recent advances in antibiotic degradation by Por-MOFs is both timely and necessary.

The literature survey was primarily conducted using the Scopus and Google Scholar databases using combinations of keywords related to Por-MOFs, including “porphyrin-MOFs”, “antibiotic degradation”, “water remediation”, and related terms such as “tetracycline” among others. In this review, we provide a comprehensive overview of recent progress in the application of porphyrin-based MOFs for antibiotic removal and degradation from aqueous environments, with particular emphasis on studies published since 2020. Only peer-reviewed publications and book chapters were considered. The scope is limited to Por-MOF-based systems for antibiotic degradation, while studies involving other pollutant categories or non-porphyrinic MOFs are discussed only by providing comparative insights. The increasing scientific interest in this area is reflected by the continuous rise in the number of publications reported in the literature over the last decade. Figure 3 illustrates the annual number of Web of Science publications related to MOF-based antibi-

otic removal and degradation between 2015 and 2025, highlighting the rapid expansion of this research field, particularly after 2021. This trend underscores the need for a comprehensive and up-to-date assessment of recent advances in porphyrin-based MOFs for antibiotic remediation.

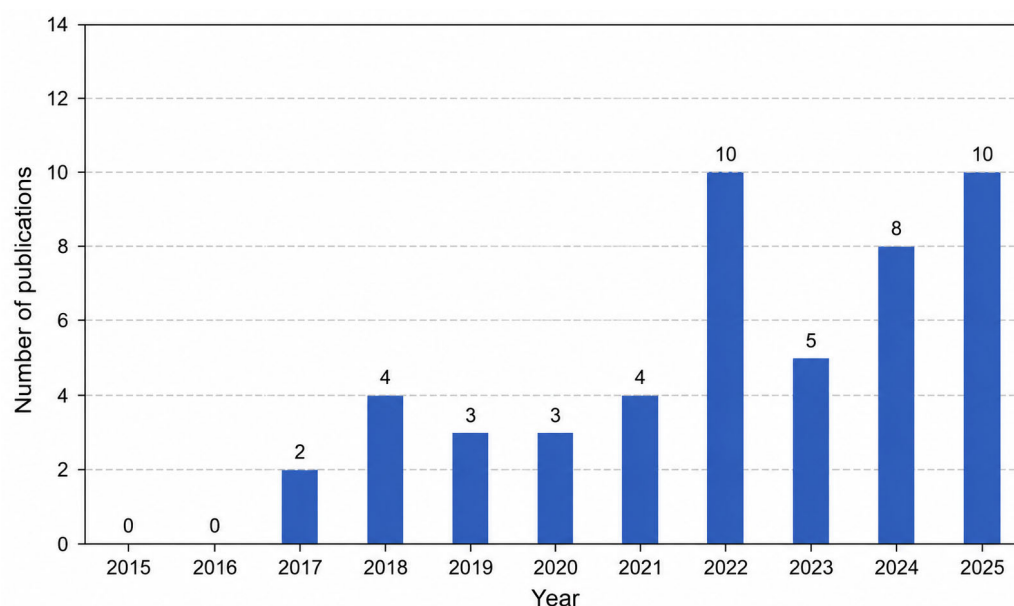


Figure 3. Annual publication trend of Web of Science-indexed studies on MOF-based materials for antibiotic removal and degradation during the period 2015–2025.

Special attention is devoted to the relationships between material design and photocatalytic performance, including the influence of ligand structure, metal node selection, framework topology, defect engineering, and heterostructure construction. The fundamental mechanisms governing antibiotic degradation, including charge-transfer pathways, reactive oxygen species generation, singlet oxygen production, photo-Fenton processes, and Z-scheme photocatalytic systems, are critically discussed. Representative studies involving the degradation of widely detected antibiotics such as ciprofloxacin, tetracycline, chloramphenicol, sulfathiazole, norfloxacin, and amoxicillin are evaluated in terms of degradation efficiency, mechanistic pathways, and practical limitations. Finally, current challenges and future perspectives are highlighted to provide guidance for the development of next-generation Por-MOF photocatalysts for sustainable water treatment and improved control of antibiotic pollution.

2. Structural Characteristics and Design Strategies of Porphyrin-Based MOFs and Performance Enhancement

A central theme throughout the recent literature is that the integration of porphyrins into MOF architectures creates a highly synergistic platform in which the exceptional photophysical properties of porphyrins are combined with the structural advantages of MOFs [57].

2.1. Strengths and Structural Characteristics of Por-MOFs

While porphyrins act as efficient visible-light absorbers and photosensitizers, MOFs provide high surface areas, tunable porosity, and well-defined catalytic environments. The resulting Por-MOFs exhibit enhanced light harvesting, improved charge separation, increased accessibility of active sites, and superior pollutant adsorption capabilities, making them particularly attractive for antibiotic degradation applications. Recent studies demonstrate that the performance of Por-MOFs arises from a deliberate integration of

adsorption and photocatalysis within a single platform. Prior to degradation, antibiotic molecules are effectively concentrated within the porous framework through a combination of π - π interactions, hydrogen bonding, electrostatic attraction, and pore confinement effects. This preconcentration step enhances the local pollutant concentration near the catalytic sites and facilitates subsequent photocatalytic degradation. Simultaneously, the strong Soret and Q-band absorption features of porphyrins enable efficient harvesting of visible light, while the MOF architecture promotes charge separation and suppresses electron-hole recombination. Together, these processes significantly improve photocatalytic efficiency compared with conventional semiconductor photocatalysts [58].

Another key advantage of Por-MOFs is their ability to generate multiple reactive oxygen species under visible-light irradiation. Among these species, singlet oxygen ($^1\text{O}_2$) is frequently identified as the dominant oxidant responsible for antibiotic degradation, although superoxide radicals ($\text{O}_2^{\bullet-}$), hydroxyl radicals ($^{\bullet}\text{OH}$), and photogenerated holes may also contribute depending on the catalyst composition and reaction conditions. The predominance of $^1\text{O}_2$ is particularly advantageous because it exhibits selective reactivity toward electron-rich functional groups commonly found in antibiotics such as fluoroquinolones and tetracyclines, promoting efficient degradation while minimizing non-selective side reactions [45].

In addition to conventional photocatalytic pathways, recent research has expanded toward multifunctional Por-MOF systems capable of operating through alternative degradation mechanisms. Fe-porphyrin frameworks can participate in photo-Fenton processes through $\text{Fe}^{2+}/\text{Fe}^{3+}$ redox cycling, thereby enhancing hydroxyl radical generation and pollutant oxidation. Similarly, Zn-based and heterostructured Por-MOFs have demonstrated efficient ligand-to-metal charge transfer and improved charge separation through the construction of heterojunctions and Z-scheme architectures. These advances illustrate the growing sophistication of Por-MOF design and highlight the transition from simple photosensitized systems toward highly engineered catalytic platforms [46,58,59].

2.2. Synthetic Procedures

Depending on the way in which the photoactive macrocyclic units are incorporated into the framework, Por-MOFs can generally be divided into two main categories. In the first approach, porphyrin molecules are encapsulated within the pores or cavities of a pre-formed MOF and act as guest species while preserving the original framework structure. In the second approach, the porphyrin units are directly integrated into the framework architecture as structural building blocks through coordination with the metal nodes, becoming an integral part of the crystalline network. The latter strategy typically promotes stronger electronic communication between the organic chromophores and the inorganic nodes, facilitating charge transfer and enhancing photocatalytic performance. Furthermore, these materials can be further engineered through the incorporation of magnetic, photothermal, fluorescent, or other functional components, enabling the development of multifunctional platforms with tailored properties for environmental, catalytic, sensing, and biomedical applications [40].

The synthesis of Por-MOFs is predominantly achieved through solvothermal or hydrothermal methods. In these approaches, metal precursors and organic ligands are dissolved in polar solvents and heated under autogenous pressure, promoting the self-assembly of highly crystalline porous frameworks. The versatility of this method allows precise control over crystal morphology, particle size, porosity, and framework topology. For example, Wang et al. recently reported the solvothermal synthesis of a three-dimensional Hf-Por-MOF for the degradation of norfloxacin in highly saline wastewater environments [60]. Despite its widespread use, solvothermal synthesis remains relatively

energy-intensive and often requires large volumes of organic solvents, which may limit scalability and increase production costs. To address these limitations, alternative synthetic strategies have been developed. Among them, microwave-assisted synthesis has emerged as a particularly attractive approach because it enables rapid and homogeneous heating, significantly reducing reaction times while maintaining high crystallinity [61]. Microwave-assisted methods can produce MOFs within minutes rather than hours and often result in smaller particle sizes and improved structural uniformity [62]. Such approaches represent important steps toward the scalable and sustainable production of Por-MOF photocatalysts.

Thus, methods summarized in Table 1 show that no single synthesis route is universally optimal for Por-MOF preparation, because the choice depends on the balance desired between crystallinity, reaction time, scalability, and green chemistry considerations [63]. Solvothermal synthesis remains the most widely used approach because it generally affords highly crystalline frameworks with well-defined porosity and good structural quality, but it is often constrained by long reaction times, high temperatures, and substantial solvent and energy consumption [64]. In contrast, microwave-assisted synthesis offers a rapid and more energy-efficient alternative, often producing smaller particles with narrower size distributions, although it may be less practical for large-scale production [65]. Green or low-solvent routes such as mechanochemical and sonochemical methods are attractive from a sustainability perspective, but they may lead to lower crystallinity or defect formation, which can affect photocatalytic performance [66]. Electrochemical and room-temperature approaches can further reduce energy demand and simplify processing, yet they are currently less versatile and applicable to fewer Por-MOF systems [67]. Overall, the comparison highlights that synthesis optimization should be guided by the intended application, with special attention to the trade-off between material quality and practical scalability [46].

Table 1. Synthetic approaches of Por-MOFs.

Method	Typical Conditions	Advantages	Disadvantages	Typical MOF Characteristics
Solvothermal	High temperature (80 to 220 °C), long reaction time	High crystallinity, excellent framework quality, suitable for large crystals	Time-consuming, high solvent consumption, high energy demand	Large crystals, high surface area
Microwave-assisted	Minutes instead of hours	Rapid synthesis, energy-efficient, smaller crystal size, narrow particle-size distribution	Limited batch size, potential non-uniform heating, specialized equipment	Nanocrystals, reduced reaction time
Mechanochemical	Grinding with little or no solvent	Green synthesis, minimal solvent, scalable	Lower crystallinity, possible structural defects	Defect-rich frameworks
Sonochemical	Ultrasonic irradiation	Fast nucleation, smaller particles, mild conditions	Limited scalability, possible framework defects	Uniform nanoparticles
Electrochemical	Metal ions generated in situ	No added metal salts, tunable growth	Complex setup, limited MOF systems	Thin films and coatings
Room-temperature synthesis	Ambient conditions	Low energy consumption, simple equipment	Longer reaction times, limited MOF diversity	Moderate crystallinity

2.3. Design Strategies

From a design perspective, the most successful Por-MOF systems are based on the incorporation of porphyrin ligands, particularly tetrakis(4-carboxyphenyl)porphyrin (TCPP), into frameworks containing metal nodes such as Zr, Hf, Fe, Cu, Zn, Ti, or lanthanide ions. The choice of both the porphyrin ligand and the metal center strongly influences the electronic structure, charge transfer behavior, adsorption properties, and photocatalytic activity of the resulting material (Figure 3). This flexibility is particularly important because antibiotic pollutants exhibit significant differences in molecular size, charge distribution, hydrophobicity, and susceptibility to oxidative degradation (Figure 3). Consequently, no single framework architecture is universally optimal, and material design must be tailored to the target contaminant and operating conditions [57]. Furthermore, structure-activity relationships have become increasingly important in the design of next-generation Por-MOF photocatalysts. Numerous studies have demonstrated that photocatalytic performance depends strongly on factors such as pore size distribution, framework topology, metal-node identity, ligand functionalization, defect density, and electronic coupling between the organic linker and inorganic cluster (Figure 4). These parameters directly influence adsorption capacity, charge separation efficiency, light absorption, and ROS generation. Consequently, Por-MOFs are no longer viewed simply as photocatalysts but rather as integrated multifunctional systems in which adsorption, photochemistry, and catalysis are intentionally combined. Structure-activity relationships have become increasingly important in the design of next-generation Por-MOF photocatalysts (Figure 3). Prior to degradation, antibiotic molecules are effectively concentrated within the porous framework through a combination of π - π interactions, hydrogen bonding, electrostatic attraction, and pore confinement effects (Figure 4). This preconcentration step enhances the local pollutant concentration near the catalytic sites and facilitates subsequent photocatalytic degradation. Numerous studies have demonstrated that photocatalytic performance depends strongly on factors such as pore size distribution, framework topology, metal-node identity, ligand functionalization, defect density, and electronic coupling between the organic linker and inorganic cluster (Figure 4).

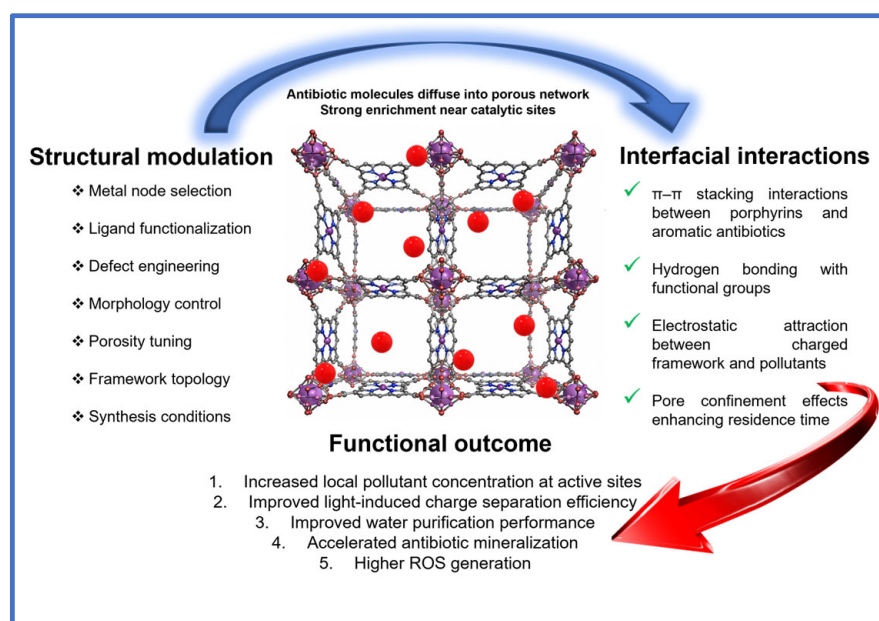


Figure 4. Structural modulation of Por-MOFs.

Among the various Por-MOF families investigated to date, Zr- and Hf-based systems, particularly the PCN-222 and PCN-224 families, have emerged as benchmark materials for antibiotic degradation [57]. Their exceptional hydrolytic stability, high porosity, and efficient charge transport properties allow them to maintain catalytic activity under prolonged operation in aqueous environments. Such stability is essential for practical water treatment applications, where framework degradation, metal leaching, and loss of catalytic activity remain significant concerns.

Overall, the literature consistently demonstrates that the remarkable performance of Por-MOFs arises from the synergistic interplay between porphyrin photochemistry and MOF structural engineering. Their tunable architectures, visible-light responsiveness, high adsorption capacities, and selective generation of reactive oxygen species make them among the most promising photocatalysts currently available for antibiotic degradation. Continued progress in framework design, heterostructure construction, and mechanistic understanding is expected to further enhance their performance and accelerate their translation toward practical environmental remediation technologies.

Recent reviews clearly indicate that the performance limitations of pristine Por-MOFs, particularly rapid charge recombination and limited quantum efficiency, have driven the development of advanced design strategies aimed at optimizing photocatalytic activity. Rather than relying on single modifications, the field has increasingly shifted toward multi-strategy integration, where structural, electronic, and interfacial properties are simultaneously engineered [57]. A key conclusion across multiple reviews is that the most effective Por-MOF systems are those that maximize charge separation while maintaining efficient ROS generation, as these two factors are fundamentally linked to photocatalytic efficiency [58]. Consequently, three major strategies have emerged as dominant: heterostructure construction, defect engineering, and compositional or ligand modification.

The comparative literature makes clear that the performance of Por-MOFs is rarely determined by porphyrin units alone; instead, catalytic efficiency is governed by how effectively the material architecture manages adsorption, charge separation, and ROS formation. Accordingly, recent work has focused on three major enhancement strategies: heterostructure construction, defect engineering, and ligand or co-catalyst modification. These approaches are not isolated. In practice, the strongest systems often combine more than one strategy, which is why the best-performing catalysts usually show both structural optimization and mechanistic complexity. This trend suggests that the field is moving from material discovery toward rational design.

Enhancement strategies for Por-MOFs focus on overcoming charge recombination and improving aqueous stability. Heterostructure formation with semiconductors like In_2S_3 creates Z-schemes that spatially separate carriers, boosting quantum efficiency [57] (Figure 5). Defect engineering introduces missing linkers to enhance light harvesting and ROS yield, particularly in Hf-TCPP systems [59]. These strategies collectively elevate degradation rates by 2–5-fold under visible light.

Current reviews methodically describe strategies to mitigate Por-MOFs' limitations like rapid e^-/h^+ recombination and suboptimal ROS yields, emphasizing heterostructures, defects, and ligand/node modulation as transformative. Afreen et al. dedicate sections to these, noting 2–5-fold activity gains via tuned band alignment [57], while Han et al. tabulate Por-MOF hybrids' superiority over pristine analogs [58]. Rabeie/Mahmoodi [68,69] quantify pH/ion tolerance improvements, and Liu et al. mechanistic insights via TAS/DFT [45]. These converge on synergistic designs yielding solar-compatible efficiencies.

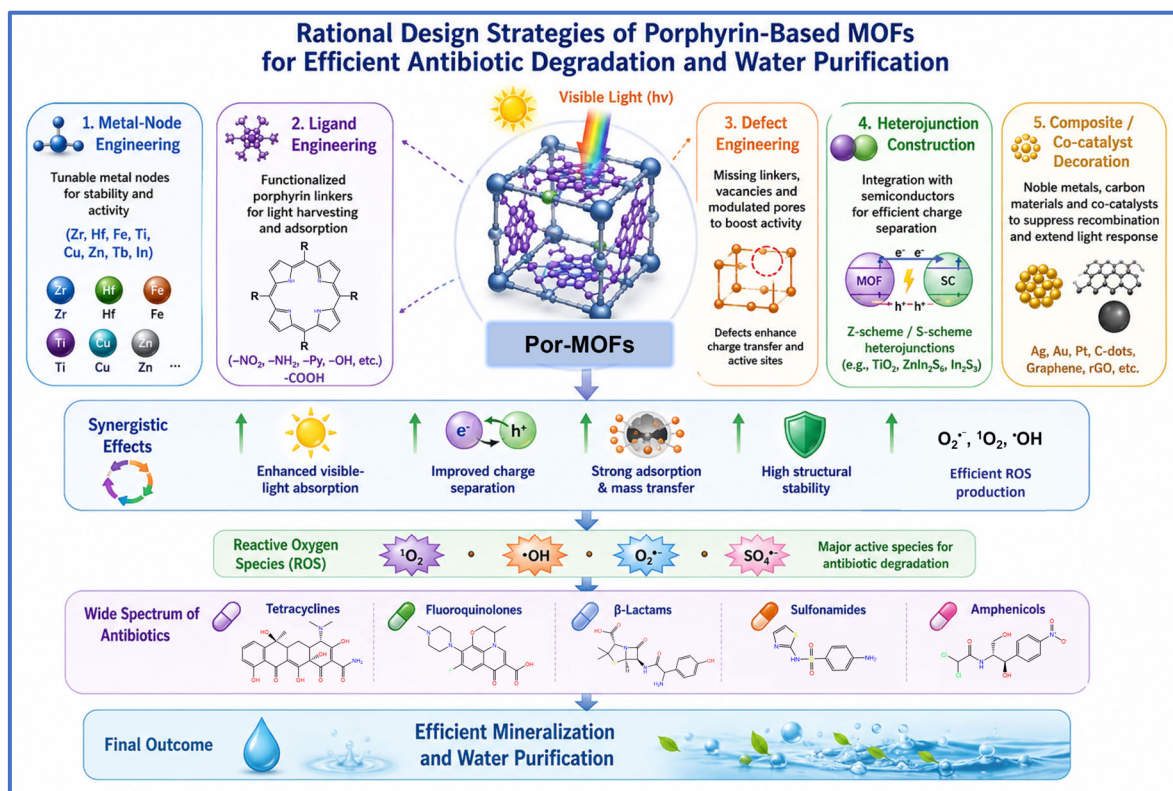


Figure 5. Por-MOF design strategies.

2.4. Heterojunctions

Heterostructure formation (Figure 5) is widely recognized as one of the most effective approaches for enhancing Por-MOF performance. Reviews highlight that coupling Por-MOFs with semiconductor materials creates Z-scheme or S-scheme systems that facilitate spatial separation of photogenerated electrons and holes, thereby reducing recombination losses [58].

These heterojunctions not only improve charge carrier lifetimes but also preserve strong redox potentials, enabling sustained ROS production. Importantly, the interface between the MOF and the semiconductor is identified as a critical factor, as it governs charge transfer directionality and efficiency [45]. As a result, heterostructure design has become a central focus in the development of next-generation photocatalysts.

Z-scheme and S-scheme heterojunctions dominate recent advances, pairing Por-MOFs with materials like ZnIn_2S_6 to direct charge flow and suppress recombination [58]. $\text{In}_2\text{S}_3/\text{PCN-224}$ exemplifies this, retaining 90+% activity over cycles via improved e^-/h^+ partitioning [70]. Reviews affirm these interfaces extend carrier lifetimes, enabling sustained ROS production [45].

2.5. Defects and Modulation

Defect engineering (Figure 5), particularly the introduction of missing-linker defects, is another widely discussed strategy in recent reviews [59]. These defects create unsaturated metal sites and localized electronic states that facilitate charge transfer and enhance catalytic activity [59].

It has been emphasized that defect sites can act as electron traps or catalytic centers, improving both adsorption and ROS generation. In addition, defect engineering can modify the band structure of Por-MOFs, lowering the energy barrier for charge transfer processes and increasing light absorption efficiency. Importantly, the interaction between defects and

co-existing species in solution, such as anions, has been shown to further enhance catalytic performance by promoting electron transfer processes [59].

Missing-linker defects in Hf-TCPP-FA promote ligand-to-metal charge transfer (LMCT) and boost norfloxacin removal by 50+% [71]. Ligand modulation in MIL-125TiTCPP creates mesopores for better mass transfer [72]. Such tuning aligns band positions for optimal ROS generation, per recent analyses.

Defects create active sites/LMCT traps, as Afreen details (missing-linkers lower E_g). Hf-TCPP-FA defects enhance PICT (93.6% NFX) via anion trapping [60]. TCPP-UiO-66(Hf)-250 leverages $\text{SO}_4^{\bullet-}$ (96% OFL) [72]. MIL-125TiTCPP mesopores from ligand removal aid diffusion/charge split (98.37% TCs); Shee/Kim links to ISC (intersystem crossing). Sutherland praises “breathing” pores (MIL-53Al, 758 mg g^{-1} AMX). Liu et al., DFT-rationalizes defect-induced band shifts.

According to Han et al., ligand tweaks tune electronics. Pillar-ZnTCPP series ROS-correlates with dimensionality (86.9% STZ) [73]. DTCx-TB10 pyrene-porphyrin transfers yield 93.09% STZ. Ag/MOF-525 SPR/Schottky (81% TC) [74]. Tb-MOF coordinates CIP/Cr(VI) synergistically (>95%). Afreen notes 1.7-fold Cr(VI) boosts via metalation. Rabeie integrates with PMS (peroxymonosulfate) for 98% OTC [68,69].

2.6. Composites and Decoration

The modification of organic linkers and metal nodes (Figure 5) is a fundamental strategy for tuning the electronic and catalytic properties of Por-MOFs. Reviews highlight that ligand functionalization can influence light absorption, energy transfer pathways, and ROS selectivity, while metal node variation directly affects redox behavior and catalytic activity [43,46].

In particular, the incorporation of additional aromatic or electron-rich ligands has been shown to enhance intraframework energy transfer, while the selection of redox-active metal centers (e.g., Fe, Cu) enables alternative degradation pathways such as photo-Fenton reactions. This level of tunability allows Por-MOFs to be tailored for specific antibiotic classes and environmental conditions [43].

Noble metals like Ag on MOF-525 induce plasmonic effects, enhancing visible absorption [74]. Carbon dot sensitization further aids charge extraction [43]. These yield synergistic gains, with reviews noting 2–3-fold activity boosts.

Advanced strategies-Z-scheme heterojunctions (e.g., In_2S_3 /PCN-224), defect engineering (Hf-TCPP-FA) [70], and ligand modulation (pyrene-TCPP)-systematically suppress recombination and boost quantum yields 2–5-fold, enabling saline tolerance and cycling stability while converging on solar-compatible remediation superior to traditional catalysts [75].

2.7. Composite Formation and Co-Catalysts

The integration of Por-MOFs with conductive or plasmonic materials represents another major advancement highlighted in reviews. The addition of noble metals or carbon-based materials can enhance light absorption, facilitate charge transfer, and suppress recombination [43] (Figure 5).

Carbon-based materials, such as carbon dots or graphene derivatives, are particularly effective as electron sinks, while metal nanoparticles introduce surface plasmon resonance effects that extend light absorption into the visible region [76]. These composite systems demonstrate significant improvements in photocatalytic efficiency, often achieving multiple-fold increases compared to pristine Por-MOFs.

Across all reviewed literature, a clear trend emerges: the future of Por-MOFs lies in rational, multi-component design rather than single-material optimization. The most

advanced systems integrate heterostructures, defects, and tailored ligand environments to achieve high efficiency, stability, and selectivity.

Importantly, reviews also emphasize that these strategies are not independent. Instead, their combined application leads to synergistic effects, where improvements in charge separation, adsorption, and ROS generation reinforce each other. This integrated design philosophy is expected to drive the next generation of Por-MOF photocatalysts toward practical applications in environmental remediation.

3. Photocatalytic Mechanism for Antibiotic Degradation

The photocatalytic performance of Por-MOFs originates from the synergistic interaction between the light-harvesting properties of porphyrin chromophores and the charge transport capabilities of the MOF framework. Upon irradiation with light of sufficient energy, photoexcitation of the porphyrin units generates excited states that promote charge separation and the formation of electron-hole pairs [35].

These charge carriers subsequently participate in a series of redox reactions that lead to the generation of ROS, which are primarily responsible for the degradation of antibiotic pollutants [77].

Unlike conventional semiconductor photocatalysts, where light absorption is mainly governed by the inorganic component, Por-MOFs utilize the porphyrin linker as the principal photosensitizing unit. Owing to their intense Soret and Q-band absorption features, porphyrins efficiently harvest visible light and transfer the absorbed energy or photogenerated electrons to neighboring metal clusters through LMCT processes. This electronic communication between the organic linker and the metal nodes promotes charge separation and suppresses electron-hole recombination, thereby enhancing photocatalytic efficiency [78]. $^1\text{O}_2$, along with $\text{O}_2^{\bullet-}$, $\bullet\text{OH}$.

The exceptional photocatalytic activity of porphyrin-based MOFs originates not only from efficient visible-light absorption but also from a series of excited-state photophysical processes that govern charge separation, energy migration, and ROS generation [79]. Following photon absorption, porphyrin linkers are excited from the electronic ground state (S_0) to higher singlet excited states (S_n), primarily through the intense Soret band (400–450 nm), before rapidly relaxing to the first singlet excited state (S_1) via internal conversion [80] (Figure 6). The S_1 state represents the primary precursor for both electron-transfer and energy-transfer processes, which ultimately determine photocatalytic efficiency. Because porphyrins possess extended π -conjugated systems and relatively long excited-state lifetimes, they function as highly efficient photosensitizers capable of harvesting visible light while minimizing non-radiative energy losses [81,82].

A key photophysical process in Por-MOFs is ISC, in which the excited singlet state undergoes spin conversion to form the triplet excited state (T_1) (Figure 6). The triplet state generally exhibits a considerably longer lifetime, typically ranging from microseconds to milliseconds depending on the framework architecture and metal coordination environment [83]. These prolonged excited-state lifetimes significantly increase the probability of intermolecular electron transfer, molecular oxygen activation, and ROS generation before charge recombination occurs (Figure 6) [84]. The efficiency of ISC can be further enhanced through the incorporation of heavy metal centers such as Hf, Zr, Fe, Co, or Cu, which increase spin-orbit coupling and facilitate spin-forbidden transitions [85] (Figure 6). Likewise, metallation of the porphyrin macrocycle itself alters the electronic configuration and often improves triplet-state formation, thereby enhancing photocatalytic activity under visible-light irradiation [80].

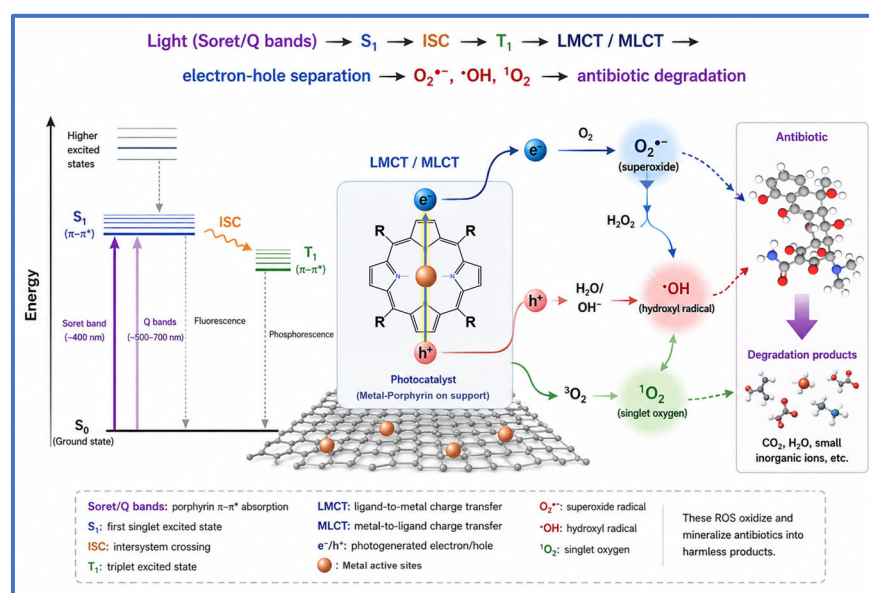


Figure 6. Charge transfer mechanism by Por-MOFs.

Once the triplet excited state has formed, two principal photochemical pathways become operative: electron transfer and energy transfer. In the electron-transfer pathway, photoexcited electrons migrate from the porphyrinic ligand toward neighboring inorganic secondary building units through LMCT (Figure 6). LMCT constitutes one of the defining electronic characteristics of Por-MOF photocatalysts because it promotes efficient spatial separation of photogenerated electrons and holes while suppressing rapid electron-hole recombination [80]. Electrons transferred to metal nodes subsequently participate in reduction reactions, most commonly involving dissolved oxygen, producing superoxide radicals ($\text{O}_2^{\bullet-}$) (Figure 6). Simultaneously, the remaining positive holes localized on the porphyrin linker oxidize water molecules or hydroxide ions to generate hydroxyl radicals ($\bullet\text{OH}$) (Figure 6). The simultaneous production of oxidative and reductive species substantially improves photocatalytic degradation efficiency and facilitates complete mineralization of antibiotic molecules [86].

The extent of LMCT strongly depends on the electronic interaction between the porphyrin linker and the metal cluster. Highly connected Zr- and Hf-based frameworks, including the PCN-222 and PCN-224 families, provide excellent electronic communication between organic and inorganic components because of their rigid coordination environment and favorable orbital overlap [87]. In contrast, defect engineering through missing-linker strategies introduces unsaturated coordination sites that lower charge-transfer barriers, enhance carrier mobility, and prolong charge-carriers' lifetimes. These structural modifications explain why defect-engineered Por-MOFs frequently outperform their fully crystalline analogues despite possessing similar chemical compositions [88].

Besides LMCT, metal-to-ligand charge transfer (MLCT) also contributes to photocatalytic activity in several transition-metal-containing Por-MOFs (Figure 6). In MLCT processes, electrons localized on partially filled d orbitals of transition-metal centers are transferred toward the conjugated porphyrin ligand following photoexcitation [83]. Although less common in Zr- or Hf-based frameworks owing to their closed-shell electronic configurations, MLCT becomes increasingly important in Fe-, Co-, Cu-, and Ru-containing porphyrinic systems, where variable oxidation states facilitate reversible electron exchange [80] (Figure 5). The coexistence of LMCT and MLCT creates bidirectional charge-transfer pathways that improve charge delocalization, extend carrier lifetimes, and facilitate continuous redox cycling during photocatalysis. In photo-Fenton systems, for example,

MLCT assists $\text{Fe}^{3+}/\text{Fe}^{2+}$ interconversion, thereby accelerating hydroxyl radical production through catalytic hydrogen peroxide activation [89].

Recent investigations have further demonstrated that ligand-to-ligand charge transfer (LLCT) and intraframework electron migration can occur in mixed-linker or dual-ligand Por-MOFs [90]. The incorporation of additional π -conjugated chromophores, including pyrene derivatives, perylene diimides, or electron-deficient aromatic ligands, establishes internal donor-acceptor architectures that promote directional charge transport throughout the framework. These electronically coupled systems reduce charge localization while facilitating rapid migration of photogenerated carriers toward catalytically active sites. Such molecular engineering strategies have proven particularly effective in Z-scheme and S-scheme heterostructures, where optimized band alignment further suppresses recombination and preserves strong oxidation and reduction potentials [87].

In addition to electron transfer, energy transfer plays an equally important role in porphyrin photocatalysis. Excitation energy may migrate through the framework via Förster resonance energy transfer (FRET), which involves long-range dipole–dipole interactions between neighboring chromophores, or through Dexter energy transfer, which proceeds via short-range orbital overlap [81,82]. The efficiency of these processes depends strongly on linker spacing, crystallographic arrangement, and framework topology [91]. Efficient energy migration allows excitation energy to be funneled toward catalytically active sites before radiative decay occurs, thereby maximizing photon utilization. Such exciton migration is particularly advantageous in highly ordered Por-MOFs, where periodic arrangements of porphyrin units create continuous pathways for energy transport across the crystalline lattice [92].

The overall photocatalytic performance of Por-MOFs is therefore governed by the delicate balance between charge generation, charge separation, charge migration, and recombination. A prolonged excited-state lifetime enables electrons and holes to participate in interfacial redox reactions rather than undergoing rapid recombination, while efficient LMCT, MLCT, and intraframework energy transfer collectively increase ROS production. The superior photocatalytic efficiency of Por-MOFs results from the synergistic integration of photophysical and photochemical processes within a highly ordered porous framework [87]. Continued optimization of these excited-state processes through rational ligand design, metal-node engineering, heterostructure construction, and defect modulation is expected to further improve photocatalytic efficiency and accelerate the practical application of Por-MOFs for antibiotic removal from contaminated water.

As depicted in Figure 7, the photocatalytic mechanism begins with photon absorption ($h\nu$) (1), which promotes an electron from the valence band (VB) to the conduction band (CB), creating a hole (h^+) in the VB and an electron (e^-) in the CB [93]. The process is effective when recombination is delayed, allowing these charge carriers to engage in surface reactions. Electrons in the CB can reduce dissolved oxygen to form superoxide radical anions ($\text{O}_2^{\bullet-}$) (4), while holes in the VB can oxidize water or hydroxide ions to generate $\bullet\text{OH}$ (2–3) [94,95]. Additional reactive species, such as peroxide radicals, may also form during these processes (5) [96,97]. Furthermore, oxygen can be transformed into $^1\text{O}_2$ (6), contributing to the oxidative degradation pathway. These ROS are highly reactive and capable of mineralizing organic pollutants into less harmful or fully oxidized products (7–9) [43,45,58,98].

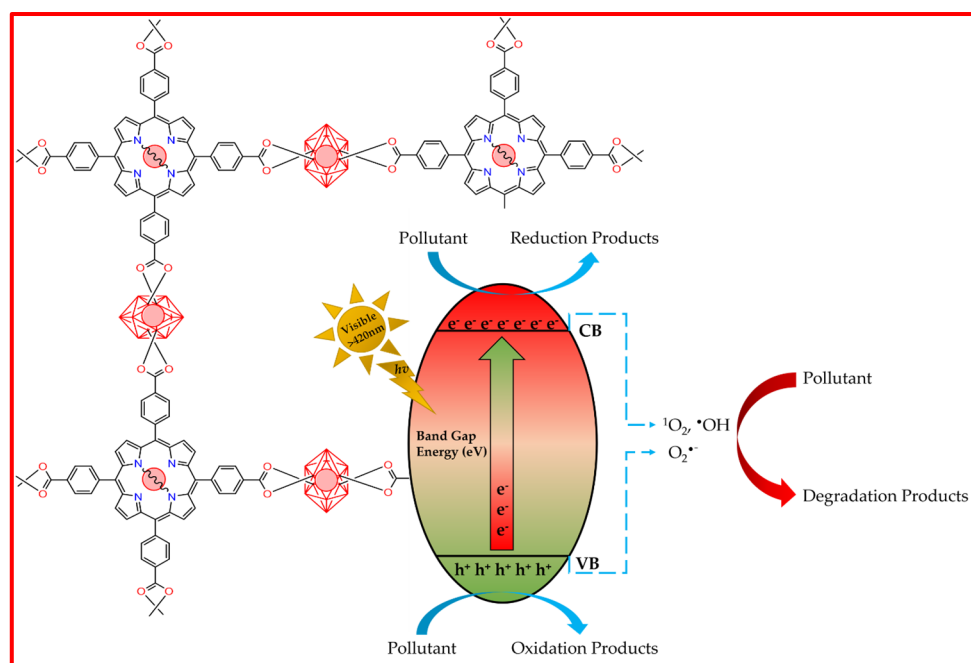
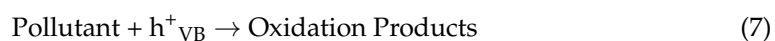
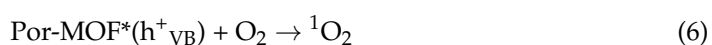
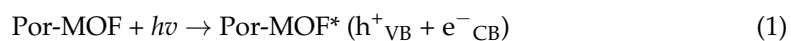


Figure 7. General degradation mechanism of pollutants with Por-MOFs.

Charge separation within the MOF is further facilitated by the migration of electrons toward the metal nodes, where reduction processes occur, while holes remain localized on the porphyrin linkers. This spatial separation minimizes recombination and enhances photocatalytic efficiency. The reduced metal centers and oxidized porphyrin units then serve as active sites for subsequent redox reactions.

A critical factor in ROS generation is the relative position of the band edges. For effective oxygen reduction to occur, the conduction band potential must be equal to or more negative than -0.046 eV, while the valence band potential must be at least $+2.27$ eV to enable water oxidation [99]. Under these conditions, interactions between the activated MOF and molecular oxygen lead to the formation of ROS such as superoxide radicals, hydroxyl radicals, and singlet oxygen, all of which are key agents in pollutant degradation [100].

Following their formation, ROS interact with organic contaminants through oxidation reactions. Hydroxyl radicals are generated via oxidation of water by valence band holes, while superoxide radicals form through the reduction of oxygen by conduction band electrons. These species initiate and propagate degradation pathways that ultimately break down complex organic molecules into simpler, less toxic compounds [57,101].



Overall, the degradation of antibiotics by Por-MOFs is governed by a complex interplay between light absorption, charge separation, ROS generation, and pollutant adsorption. The ability to integrate these processes within a single, tunable porous framework represents one of the major advantages of Por-MOFs and explains their growing prominence as advanced photocatalysts for environmental remediation.

4. Antibiotic Degradation by Porphyrin-Based MOFs

The antibiotic classes discussed in this section follow the classification presented in Figure 2 and were selected based on their environmental prevalence, persistence, and degradation complexity [102–107]. Different antibiotic families exhibit distinct molecular structures, functional groups, and physicochemical properties, which influence their adsorption behavior, susceptibility to oxidation, and degradation pathways. Consequently, the performance of Por-MOFs varies considerably across antibiotic classes, providing valuable insights into the structure-activity relationships governing photocatalytic remediation. Tetracyclines are discussed first because of their widespread occurrence and structural complexity, followed by fluoroquinolones, sulfonamides, β -lactams, and amphenicols [69–73].

4.1. Tetracyclines

Tetracyclines represent one of the most frequently detected classes of antibiotics in aquatic environments due to their extensive use in human and veterinary medicine. Their complex polycyclic structure, multiple ionizable functional groups, and strong tendency to form complexes with metal ions make them challenging targets for conventional treatment technologies. Consequently, tetracyclines have become one of the most extensively studied model pollutants for evaluating the performance of Por-MOF photocatalysts. The high efficiency of Por-MOFs toward tetracycline degradation is primarily attributed to the synergistic combination of adsorption and photocatalysis. The aromatic structure of tetracyclines promotes strong π - π interactions with porphyrinic linkers, while hydrogen bonding and electrostatic interactions facilitate pollutant preconcentration within the porous framework. This close proximity between the adsorbed pollutant and the catalytic sites significantly enhances degradation rates under visible-light irradiation [70]. Among the reported systems, Zr-based Por-MOFs such as PCN-224 have demonstrated exceptional performance, achieving rapid tetracycline adsorption followed by efficient photocatalytic degradation through singlet oxygen-mediated pathways [108]. Similarly, Ti-based porphyrinic frameworks exhibit excellent activity due to enhanced visible-light harvesting, efficient charge separation, and mesoporous architectures that facilitate mass transport [109]. Recent studies have also demonstrated that heterojunction engineering can further improve tetracycline degradation by suppressing charge recombination and increasing ROS production. In particular, Z-scheme architectures have shown enhanced photocatalytic stability and sustained degradation performance over multiple catalytic cycles.

Overall, the literature consistently identifies tetracyclines as ideal model compounds for evaluating Por-MOF performance because their degradation strongly depends on adsorption capacity, ROS generation efficiency, and catalyst stability. Under optimized conditions, degradation efficiencies exceeding 90% are frequently reported within relatively short irradiation times [68,69].

4.2. Fluoroquinolone Antibiotics

Fluoroquinolones, including ciprofloxacin and norfloxacin, are among the most persistent and environmentally relevant antibiotic contaminants [62]. Their aromatic quinolone core, fluorinated substituents, and high resistance to biodegradation contribute to their widespread detection in surface waters, wastewater effluents, and sediments. Moreover,

their persistence is closely linked to the development and dissemination of antimicrobial resistance, making their removal a priority in advanced water treatment technologies. The degradation of fluoroquinolones by Por-MOFs is largely governed by selective ROS-mediated oxidation pathways. In contrast to tetracyclines, fluoroquinolone degradation often relies heavily on singlet oxygen due to the high reactivity of the quinolone ring system toward electrophilic oxidation. Consequently, Por-MOFs capable of efficiently generating $^1\text{O}_2$ generally exhibit superior degradation performance. Recent studies have highlighted the effectiveness of both Zr- and Hf-based porphyrinic frameworks for fluoroquinolone removal. Defect-engineered Hf-Por-MOFs have shown particularly promising performance in saline wastewater environments, where missing-linker defects enhance charge transfer, adsorption capacity, and ROS generation [57]. Similarly, Fe-containing Por-MOFs can exploit photo-Fenton pathways, producing multiple reactive species through $\text{Fe}^{2+}/\text{Fe}^{3+}$ redox cycling and thereby accelerating antibiotic degradation. Such systems often achieve near-complete removal within less than one hour of visible-light irradiation [60]. The literature further demonstrates that fluoroquinolone degradation is highly sensitive to framework electronic structure, emphasizing the importance of charge-transfer processes such as ligand-to-metal charge transfer and photoinduced intervalence charge transfer. These findings highlight the critical role of metal-node selection in determining photocatalytic performance.

4.3. β -Lactams and Sulfonamides

Sulfonamides and β -lactam antibiotics constitute another important class of emerging contaminants frequently detected in wastewater treatment plant effluents and agricultural runoff. Although both classes exhibit lower environmental persistence than fluoroquinolones, their continuous release into aquatic environments maintains their ecological relevance and contributes to the propagation of antibiotic resistance.

The degradation of these antibiotics illustrates the versatility of Por-MOFs, which can operate through multiple photocatalytic and non-photocatalytic pathways. Unlike tetracyclines and fluoroquinolones, whose degradation is predominantly driven by ROS generation under light irradiation, several Por-MOF systems have demonstrated the ability to degrade β -lactam antibiotics through charge-transfer processes even under low-light or dark conditions. For example, Zn-based porphyrinic frameworks have been reported to facilitate amoxicillin degradation through ligand-to-metal charge transfer processes that activate the antibiotic without requiring continuous photoirradiation [110]. Meanwhile, dual-ligand Por-MOF architectures have shown enhanced degradation of sulfonamides through improved energy-transfer processes and more efficient ROS generation. Such systems demonstrate how rational ligand engineering can significantly influence photocatalytic behavior. An important advantage of Por-MOFs for these antibiotic classes is their ability to combine selective adsorption with catalytic degradation. Coordinatively unsaturated metal sites and tailored pore environments promote strong interactions with antibiotic molecules, increasing local concentrations near catalytic centers and facilitating efficient degradation. Consequently, removal efficiencies exceeding 90% are commonly reported under optimized conditions [75].

Overall, studies on sulfonamides and β -lactams highlight the multifunctional nature of Por-MOFs and demonstrate how subtle modifications in framework composition can alter degradation pathways, ROS selectivity, and overall catalytic performance.

4.4. Performance in Real Wastewater

To date, the vast majority of Por-MOF studies for antibiotic degradation have been performed in simplified matrices that contain a single pollutant in ultrapure or buffered

water, whereas only a small number of reports use secondary effluents, industrial wastewaters or simulated complex matrices [111]. In these more realistic systems, photocatalytic rates and apparent removal efficiencies are generally lower than in pure water, which is consistently attributed to competitive adsorption, reactive oxygen species scavenging and reduced light penetration caused by coexisting inorganic ions and natural organic matter (NOM) [112]. These observations underline that high degradation percentages reported under ideal laboratory conditions should be regarded as an upper bound, and that matrix effects remain one of the main barriers for translating Por-MOFs into practical wastewater treatment technologies [113].

Real wastewaters contain substantial levels of chloride, sulfate, bicarbonate, carbonate, nitrate and phosphate, together with Ca^{2+} , Mg^{2+} and trace heavy metals, all of which can interact with Por-MOFs and with photogenerated species [114–117]. Anions can compete with antibiotics for adsorption sites, form outer-sphere complexes with unsaturated metal nodes or act as electron donors or scavengers that modulate ROS generation, as illustrated by sulfate [72], which can enhance antibiotic degradation in Hf- and Zr-porphyrin MOFs by donating electrons into Hf clusters yet also compete for surface sites. NOM and dissolved organic matter further complicate the situation, since humic-like substances and other chromophoric dissolved organic matter (DOM) can both act as auxiliary photosensitizers and as strong radical scavengers, with several studies concluding that DOM screens light, consumes $\bullet\text{OH}$ and $^1\text{O}_2$ and thereby slows antibiotic degradation in photocatalytic systems [118].

The influence of pH is twofold, affecting both antibiotic speciation and Por-MOF surface charge, and has been shown to strongly modulate photochemical transformation kinetics of fluoroquinolones such as ciprofloxacin and norfloxacin [119]. For many antibiotic classes, zwitterionic forms near neutral to mildly alkaline pH exhibit higher photolytic and photocatalytic transformation rates, while extreme pH values can destabilize MOF frameworks, alter band positions and change adsorption selectivity [120]. Ionic strength controls the thickness of the electrical double layer around charged frameworks; increased salinity tends to compress the double layer and reduce long-range electrostatic attraction, which can lower adsorption efficiencies, although defect-engineered Hf- and Zr-Por-MOFs have been specifically designed to retain activity in highly saline wastewaters [119].

Por-MOF photocatalysis relies on dissolved oxygen as the main terminal electron acceptor for generating superoxide and singlet oxygen, so DOM concentration is a critical parameter that is rarely controlled in real wastewater tests [74]. In aerated model solutions, abundant oxygen facilitates ligand-to-metal charge transfer LMCT and ROS formation, whereas in oxygen-depleted matrices, for example anaerobic industrial effluents, the scarcity of O_2 limits both $\text{O}_2^{\bullet-}$ and $^1\text{O}_2$ production and shifts the mechanism toward hole-driven oxidation and minor pathways involving added oxidants such as persulfate or H_2O_2 [121]. A few Por-based photocatalysts immobilized on supports have shown promising degradation of antibiotics under air bubbling or natural aeration, but systematic optimization of DOM levels for Por-MOF systems remains largely unexplored [118].

Finally, catalyst fouling is an important but underreported issue for Por-MOFs in real wastewater, where NOM, biofilms, inorganic precipitates and colloidal particles can irreversibly block pores and shield photoactive sites [122]. Powdered Por-MOFs dispersed in complex matrices can suffer from gradual loss of accessible surface area, photobleaching of porphyrin units and metal or ligand leaching, while immobilized Por-MOFs on membranes, aerogels or monoliths are additionally subject to surface fouling layers that reduce light penetration and mass transfer [123]. Only a small number of porphyrin photocatalyst studies report stable cycling in the presence of NOM and mixed pollutants, often requiring

aggressive oxidative regeneration, which suggests that robust anti-fouling designs and regeneration protocols are essential for realistic deployment [124].

5. Comparative Studies

The comparative evidence collected in Table 2 shows that Por-MOFs exhibit strong but highly variable performance depending on the pollutant class, metal node, and degradation pathway. A general pattern emerges in which the most effective systems are those that combine strong adsorption affinity with efficient charge separation and reactive oxygen species generation. In this sense, Table 2 does not merely list individual catalysts, but rather reveals how structural design governs catalytic outcomes across different antibiotic targets (Figure 2). Although the reported efficiencies are not always directly comparable because of different irradiation conditions (Table 2), pollutant concentrations, and reaction times, the data still provide a useful framework for identifying the most successful design principles. Xenon lamps (300–500 W) predominate across 80% of entries (Table 2), paired with >400–420 nm filters to target porphyrin excitation while blocking UV degradation. The consistent wavelength cutoff optimizes visible-light-driven charge transfer in Cu/Fe/Hf/Zr-based MOFs. AgMOF-525 [74] and PCN-224 [108] use higher-power 500 W setups, suggesting intensity needs for dye/antibiotic degradation. Notable outliers include dark-condition Zn-porphyrin MOF (room-temperature catalysis) [110] and targeted 520 nm LED for Zn-TPyPNO₂ [125], highlighting versatility beyond standard Xe systems.

Table 2. Comparative studies of antibiotic degradation by por-MOFs

Antibiotic	Porphyrin-MOF Catalyst	Porphyrin	Metal Node	Degradation Mechanism	Removal Efficiency (%) / Irradiation Parameters	Ref
Oxytetracycline (OTC), Tetracycline (TCL), Norfloxacin (NFX)	2D Cu-TCPP nanosheets	TCPP	Cu	Adsorption plus visible-light photocatalysis	OTC 46.7%, TCL 86.3%, NFX 44.3% in 360 min; 300 W Xe, >400 nm	[126]
Tetracycline (TC), Ciprofloxacin (CIP)	PCN-224 (300 nm)	TCPP	Zr	Electrostatic attraction, H-bonding, π - π interactions; visible-light-generated ¹ O ₂ for photocatalytic regeneration	TC 99.1% in 4 min; 500 W Xe, >420 nm	[108]
Amoxicillin	Zn-porphyrin MOF	TCPP	Zn	Dark catalytic degradation at room temperature; charge transfer from carboxyphenyl porphyrin ligand to Zn ²⁺ vacant d orbitals	97.3% in 90 min; Dark	[110]
Ciprofloxacin (CIP)	Fe-TCPP-3	TCPP	Fe	Visible-light photo-Fenton; e ⁻ transfer reduced Fe ³⁺ to Fe ²⁺ ; h ⁺ , e ⁻ , •OH, O ₂ • ⁻ and ¹ O ₂ involved	73% in 30 min; 300 W Xe, >400 nm	[62]
Ofloxacin (OFL)	TCPP-UiO-66(Hf)-250	TCPP	Hf	O ₂ • ⁻ , ¹ O ₂ and SO ₄ • ⁻ dominated; sulfate acted as electron donor and promoted charge transfer via Hf clusters	>96% in 60 min; Visible Light	[72]
Tetracycline (TC); also, Rhodamine B as model pollutant	Ag/MOF-525	TCPP	Zr	Ag nanoparticles form Schottky barrier and SPR effect, enhance visible-light absorption and suppress e ⁻ /h ⁺ recombination; h ⁺ and O ₂ • ⁻ are main active species	TC 81% in 200 min, RhB 91% in 60 min; 500 W Xe, >420 nm	[74]
Norfloxacin (NFX)	Hf-TCPP-FA	TCPP	Hf	Missing-linker defects promoted PICT/LMCT; O ₂ • ⁻ , ¹ O ₂ and •OH dominated; anion trapping enhanced adsorption and charge transfer	93.6% in 60 min; 350 W Xe, >400 nm	[60]
Tetracycline hydrochloride (TC)	In ₂ S ₃ /PCN-224 (optimized ISP-70)	TCPP	Zr	Direct Z-scheme heterojunction improves e ⁻ /h ⁺ separation; O ₂ • ⁻ and h ⁺ are dominant active species	~82% in 40 min; 300 W Xe, >420 nm	[70]

Table 2. Cont.

Antibiotic	Porphyrin-MOF Catalyst	Porphyrin	Metal Node	Degradation Mechanism	Removal Efficiency (%) / Irradiation Parameters	Ref
Ciprofloxacin (CIP) with Cr(VI)	Tb-MOF	TCPP	Tb	Synergistic removal: CIP coordinates Tb ³⁺ , promotes Cr(VI) adsorption; Cr(VI) accepts electrons; O ₂ ^{•−} dominant, ¹ O ₂ also contributes	>95% in 90 min; Xenon lamp	[127]
Oxytetracycline (OTC)	MIL-125Ti/TCPP-300	TCPP	Ti	Ligand modulation plus selective ligand removal creates mesopores and improves visible-light absorption/charge separation; O ₂ ^{•−} , ¹ O ₂ , [•] OH and h ⁺ participate, with ¹ O ₂ dominant	OTC 92.18% in 1 h, 98.37% for six tetracyclines; Visible Light >420 nm	[109]
Sulfathiazole and norfloxacin (STZ and NFX)	2DTcpp, 3DPyTcpp and 3DNDITcpp Pillar-layered metal-organic framework	TCPP	Zn	Photo-induced electron transfer interactions between ligands enhance photodynamic sterilization and photocatalytic degradation, 3DNDITcpp > 3DPyTcpp > 2DTcpp. This trend is identical to their ROS generation capabilities.	STZ and NFX for 2DTcpp, 3DPyTcpp, and 3DNDITcpp were 20.53/53.6%, 28.6/56.9%, and 86.9/71.5% in 40 min; Xenon lamp	[73]
Chlortetracycline hydrochloride (CTC)	PCN-222/Zn ₃ In ₂ S ₆ (PCNZIS-2)	TCPP	Zr	S-scheme heterojunction with internal electric field enhances directional charge transfer; O ₂ ^{•−} and h ⁺ dominate, [•] OH secondary	89% in 180 min; 300 W Xe	[128]
Sulfathiazole	DTCx-TB10 series (X = 3, 4, 5, 6, 7, 8), Zr-TCPP, and Zr-TBAPy	TCPP and pyrene	Zr	Porphyrin/pyrene-based energy transfer enhances visible-light photocatalytic degradation with ¹ O ₂ dominant ZrTBAPy < Zr-TCPP < TC8-TB10 < TC5-TB10 < TC6-TB10 < TC7-TB10 < TC3-TB10 < TC4-TB10	93.09% for TC4-TB10 in 120 min; PL-X500D Xe, Full spectrum	[75]
Trimethoprim; ciprofloxacin; ofloxacin; amoxicillin	UDS-2 (3D-Zn ₂ TPyP(NO ₂) ₂) _n	ZnTPyP	Zn	¹ O ₂ -driven photocatalysis/ photosensitization under visible light; scavenger tests showed no role for h ⁺ , O ₂ ^{•−} , or [•] OH	100% for ciprofloxacin, ofloxacin, and amoxicillin in 100 min; trimethoprim much slower, 700 min; 520 nm LED, 520 nm	[125]
Chloramphenicol	ITO-TCPP/Cu-PorMOF Dual-porphyrin Z-scheme heterostructure	TCPP/Cu-PorMOF	Cu	Donor-acceptor Z-scheme photoelectrochemical strategy for combined detection and degradation: H ⁺ + e [−] + CAP → degradation products	77.1% in 150 min; 300 W Xe, >400 nm	[129]

The earliest entry, the 2D Cu-TCPP nanosheets, already illustrates the importance of coupling adsorption with photocatalysis. This system was able to remove tetracycline with an efficiency of 86.3%, while also showing meaningful adsorption capacities for oxytetracycline, tetracycline, and norfloxacin. The relatively strong performance is significant because it indicates that a simple two-dimensional porphyrin framework can still be highly effective when its morphology promotes pollutant uptake and interfacial contact. However, compared with later generations of catalysts, this system relies more heavily on physical adsorption and less on advanced charge-regulation strategies, suggesting that it represents an important but early stage in the evolution of porphyrin-MOF photocatalysts [126].

Next, the PCN-224 represents a clear step forward because it combines rapid adsorption with visible-light-driven regeneration. The catalyst achieved 99.1% adsorption of tetracycline in just 4 min and retained high degradation efficiency during reuse, with 92% degradation for tetracycline and 84% for ciprofloxacin in regeneration tests (Figure 8a). This behavior highlights the value of electrostatic attraction, hydrogen bonding, and π - π stacking in preconcentrating antibiotics near the active surface. More importantly, the visible-light-generated singlet oxygen provides a clean and selective oxidative route that

supports regeneration rather than simple one-time capture. Among the entries in Table 2, PCN-224 is one of the best examples of a material that integrates fast adsorption with reusable photocatalytic functionality (Figure 8b) [108].

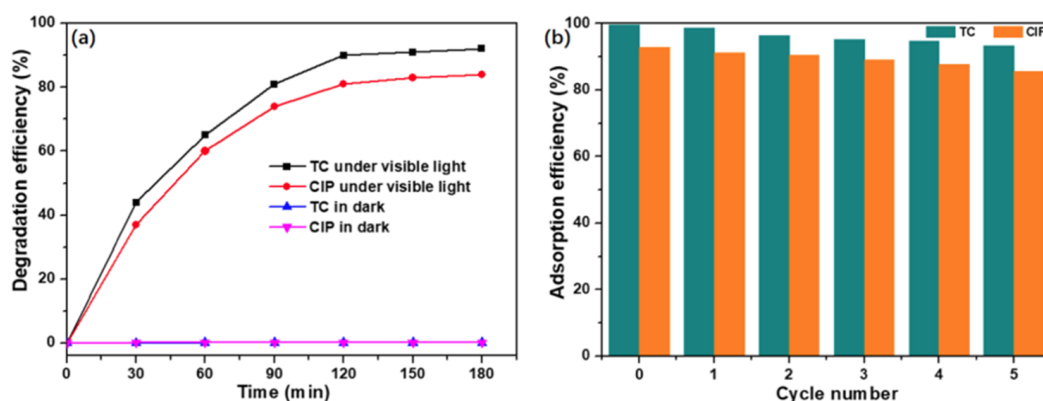


Figure 8. Photocatalytic regeneration (a) and reusability (b) of 300 nm-PCN-224, produced from ref [108].

Continuing with the Zn-Por-MOF for amoxicillin stands out because it operates effectively at room temperature in the dark, reaching 97.3% degradation. This is mechanistically distinct from the other systems because its activity is attributed to charge transfer from the porphyrin ligand to the vacant Zn orbitals rather than to visible-light excitation alone (Figure 9). The result is important for comparative purposes because it shows that Por-MOFs are not restricted to light-driven pathways. Instead, they can also support thermally activated catalytic processes when the ligand-metal electronic interaction is favorable. This broadens the functional range of porphyrin frameworks and suggests that metal node choice can radically alter catalytic behavior [110].

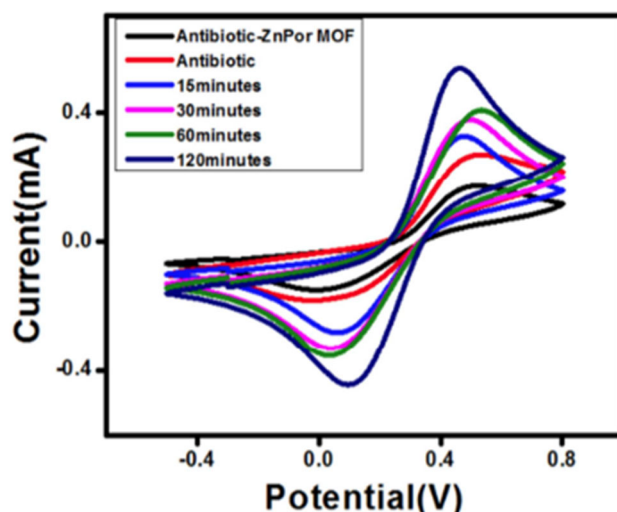


Figure 9. Amoxicillin degradation in PBS using a working electrode of bare ITO, an auxiliary electrode of platinum (Pt) wire, and a reference electrode of saturated Ag/AgCl with 5 mM $[\text{Fe}(\text{CN})_6]^{3-/4-}$ as a redox mediator, produced from ref [110].

Fe-TCPP-3 illustrates the value of photo-Fenton chemistry in antibiotic degradation. It removed 73% of ciprofloxacin in 30 min, which is lower than the best-performing adsorption-assisted systems, but it operates through a highly reactive redox cycle involving $\text{Fe}^{3+}/\text{Fe}^{2+}$ conversion and the simultaneous participation of h^+ , e^- , $\bullet\text{OH}$, $\text{O}_2^{\bullet-}$, and $^1\text{O}_2$. This broad radical spectrum makes the system mechanistically powerful, even if

the raw removal percentage is not the highest in Table 2. In comparative terms, Fe-TCPP-3 is important because it shows that effective degradation can be achieved through radical richness rather than extreme adsorption capacity. The result also confirms that metal-node redox activity remains a central advantage of porphyrin-MOFs in pollutant oxidation [62].

Moving on, the Hf-based systems offer some of the strongest evidence for the usefulness of defect engineering and sulfate-assisted charge transfer. In TCPP-UiO-66(Hf)-250, removal of ofloxacin (OFL) exceeded 96%, and the process was dominated by $O_2^{\bullet-}$, 1O_2 , and $SO_4^{\bullet-}$. Here, sulfate acted as an electron donor and enhanced charge transfer through the Hf clusters, which is a valuable mechanistic distinction because it shows that the reaction medium itself can actively contribute to photocatalytic performance [72]. Similarly, Hf-TCPP-FA achieved 93.6% norfloxacin removal through missing-linker defects that promoted photoinduced charge transfer and anion trapping. Together, these two entries suggest that Hf-based Por-MOFs are especially effective when local defect chemistry and interfacial electron migration are deliberately tuned [60].

Ag/MOF-525 shows how noble metal decoration can improve performance through plasmonic and electronic effects. Its tetracycline removal efficiency reached 81% in 200 min, while Rhodamine B degradation was 91% in 60 min. Although this performance is not the highest in Table 2, the system is still valuable because Ag nanoparticles create a Schottky barrier and strengthen visible-light absorption through surface plasmon resonance. The main active species were h^+ and $O_2^{\bullet-}$, indicating that the catalyst relies on suppressed recombination and enhanced interfacial electron flow rather than on a single dominant ROS pathway. This makes the system a representative example of how metal decoration can improve an already functional porphyrin scaffold [74].

Next, the In_2S_3 /PCN-224 heterojunction, optimized as ISP-70, provides a more advanced example of structural integration. It achieved about 82% removal of tetracycline hydrochloride in 40 min and maintained more than 90% of its activity after four cycles. Its direct Z-scheme architecture improves electron-hole separation and preserves strong oxidation power through $O_2^{\bullet-}$ and h^+ as the dominant active species. Compared with the earlier single-phase systems, this result demonstrates the benefit of combining a Por-MOF with an inorganic semiconductor to create a more efficient directional charge-transfer platform. The recyclability result is particularly important because it begins to address one of the main limitations of photocatalytic materials in practical use [70].

The Tb-MOF system extends the comparative picture by showing that Por-MOFs can support multifunctional removal strategies. In this case, ciprofloxacin coordinates to Tb^{3+} , which enhances Cr(VI) adsorption and allows a synergistic removal process, with more than 95% elimination within 90 min (Figure 10). The main active species was $O_2^{\bullet-}$, with 1O_2 also contributing. This entry is notable because the removal mechanism is not limited to oxidation of the antibiotic alone, but instead integrates contaminant capture and simultaneous reduction in another pollutant species. Such multifunctionality is highly relevant for real wastewater systems, where mixed pollutants are the norm rather than the exception [127].

MIL-125(Ti)TCPP-300 is one of the most impressive entries in Table 2 because it combines high efficiency with unusually broad substrate scope. It removed oxytetracycline at 92.18% in 1 h and achieved 98.37% degradation across six tetracycline antibiotics. Its performance was attributed to ligand modulation and selective ligand removal, which created mesopores and improved visible-light absorption and charge separation. The dominant involvement of 1O_2 , along with $O_2^{\bullet-}$, $\bullet OH$, and h^+ , indicates a multiradical oxidation environment. This system demonstrates that rational pore and ligand engineering can produce catalysts with both fast kinetics and broad applicability, making it one of the most versatile examples in Table 2 [109].

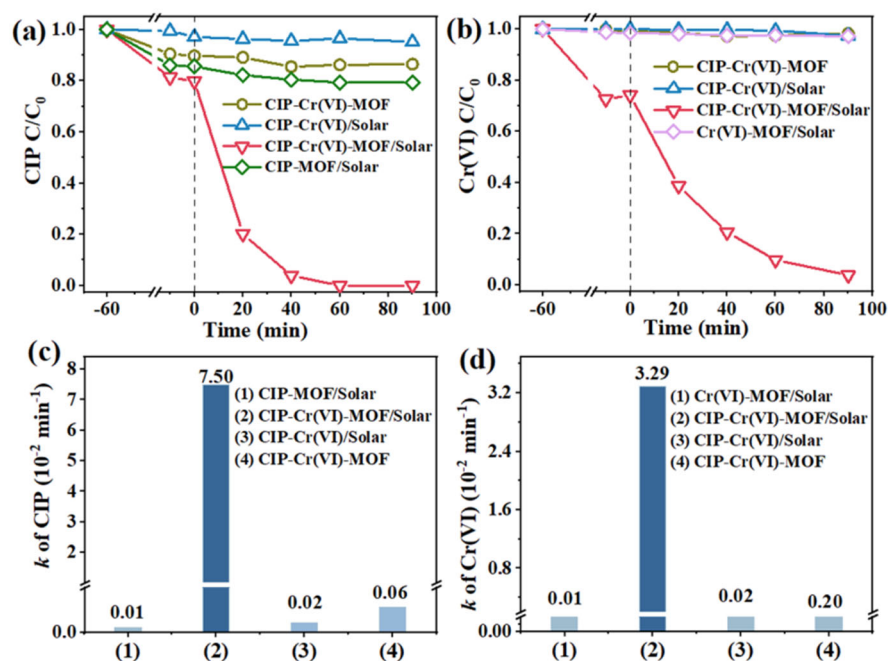


Figure 10. (a) CIP degradation efficiency, (b) Cr(VI) reduction efficiency, (c) degradation rate constant (k) for CIP, and (d) reduction rate constant for Cr(VI) in various systems, produced from ref [127].

Another zirconium MOF, the pillar-layered Zn-MOF series, including 2DTcpp, 3DPyTcpp, and 3DNDITcpp, is especially useful for comparing the effect of ligand architecture on activity. Their degradation rates increased in the order 2DTcpp < 3DPyTcpp < 3DNDITcpp, matching the trend in ROS generation capabilities. For sulfathiazole, the corresponding values were 20.53%, 28.6%, and 86.9%, while for norfloxacin the values were 53.6%, 56.9%, and 71.5%. This sharp performance spread shows that ligand-level electronic communication can be just as important as metal-node selection. It also reinforces the idea that photodynamic sterilization and photocatalytic degradation are tightly linked to the ability of the framework to support efficient intralayer electron transfer [73].

The PCN-222/ $Zn_3In_2S_6$ heterostructure and the dual-ligand Zr-MOFs further confirm the growing importance of advanced energy-transfer systems. PCN-222/ $Zn_3In_2S_6$ removed 89% of chlortetracycline (CTC) in 180 min, with $O_2^{\bullet-}$ and h^+ identified as the dominant species. Its S-scheme heterojunction and internal electric field promote directional charge transfer, which is critical for maintaining oxidative power [128]. In parallel, the porphyrin/pyrene-based sulfathiazole system achieved a best efficiency of 93.09% for TC4-TB10, and the sequence of activity clearly showed that the largest gains came from enhanced energy transfer among the ligands. These examples indicate that recent work has moved toward increasingly sophisticated electronic design, rather than relying only on simple adsorption or basic photocatalysis [75].

The most recent entries highlight the expansion of Por-MOFs into photosensitization and combined detection-degradation platforms. UDS-2 achieved rapid transformation of ciprofloxacin, ofloxacin, and amoxicillin at 100 ppb within about 100 min (Figure 11), and it did so through a 1O_2 -driven pathway with no apparent role for h^+ , $O_2^{\bullet-}$ or $\bullet OH$. This selectivity is valuable because it shows that singlet oxygen can be sufficient for effective water treatment when the framework is optimized for photosensitization [125].

Chloramphenicol removal by the ITO-TCPP/Cu-PorMOF dual-porphyrin Z-scheme heterostructure reached 77.1% in 150 min [129]. While the numerical efficiency is more moderate than some other entries, the system is notable, because it couples detection with

degradation in a photoelectrochemical format, which points toward integrated analytical-remediation technologies [129].

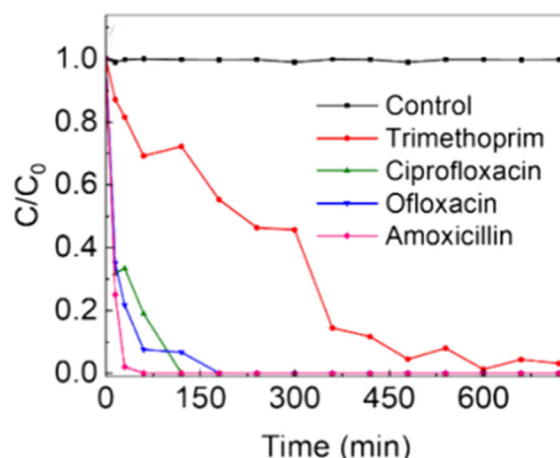


Figure 11. Photodegradation of antibiotics, produced from ref [125].

Overall, the comparative Table 2 shows that the most effective Por-MOFs are not necessarily those with the highest intrinsic porphyrin content, but rather those that best integrate adsorption, electronic coupling, and ROS control. Zr- and Hf-based systems generally perform strongly because of their stable clusters and compatibility with structured charge-transfer pathways, while defect-rich, hetero-structured, or ligand-modulated frameworks often outperform simpler architectures. Most entries in Table 2 use TCPP as the porphyrin linker because it is the most widely established and versatile porphyrinic building block for MOF construction. Its tetracarboxylate functionality enables robust coordination with a broad range of metal nodes, especially Zr, Hf, Fe, Cu, and Zn, while its strong visible-light absorption and favorable photophysical properties make it highly effective for photocatalytic applications. In addition, TCPP is commercially accessible, structurally well studied, and synthetically adaptable, which is why it repeatedly appears as the benchmark ligand in comparative studies of porphyrin-based MOFs. The summary also makes clear that $^1\text{O}_2$, $\text{O}_2^{\bullet-}$, $\bullet\text{OH}$ and multiradical pathways each have distinct advantages depending on the pollutant and catalyst design. In practical terms, this means that future progress will likely depend less on discovering new porphyrin motifs alone and more on engineering how the porphyrin unit interacts with the metal node, the lattice defects, and any secondary components in the composite.

Degradation Pathways, Mineralization and Toxicity Assessment of Transformation Products

Although photocatalytic degradation efficiency is commonly expressed as the disappearance of the parent antibiotic, this parameter alone does not provide a complete assessment of environmental safety. During photocatalytic oxidation, antibiotics undergo a sequence of hydroxylation, dealkylation, deamination, desulfonylation, decarboxylation, and ring-opening reactions before complete mineralization to CO_2 , H_2O , and inorganic ions [130–132]. Consequently, recent studies increasingly evaluate photocatalytic performance through three complementary criteria: (i) identification of degradation intermediates, (ii) mineralization efficiency, and (iii) toxicity evolution of the transformation products.

Recent advances in LC-MS and UPLC-HRMS have enabled detailed elucidation of degradation pathways in porphyrin-based MOFs. For example, a dual-ligand TCPP/TBAPy Zr-MOF designed for sulfathiazole degradation identified fourteen transformation products (P1–P14), revealing sequential S–N bond cleavage, amino oxidation, sulfonamide hydrolysis, and thiazole ring opening before formation of low-molecular-

weight organic acids and ultimately CO₂ [75]. Likewise, a MIL-125(Ti)-TCPP photocatalyst used for oxytetracycline degradation identified eleven intermediates (P1-P11) arising from successive demethylation, hydroxyl loss, and fragmentation of the tetracyclic backbone before complete oxidation [109]. These studies clearly demonstrate that antibiotic degradation proceeds through multiple oxidation steps rather than a direct conversion of the parent molecule into mineralized products.

Importantly, degradation efficiency should not be confused with mineralization. In the TCPP/TBAPy Zr-MOF system, 93.09% sulfathiazole removal was achieved within 120 min, whereas TOC removal reached only approximately 27%, indicating that most of the carbon remained in soluble organic intermediates despite the disappearance of the parent antibiotic [75]. Similar discrepancies have been reported in electro-Fenton oxidation of sulfathiazole, where high degradation efficiencies were accompanied by only 16% TOC removal, as well as in MIL-125(Ti)-TCPP photocatalysts for tetracycline antibiotics, where nearly complete degradation was still associated with measurable residual TOC [109]. Likewise, a PCN-222/Zn₃In₂S₆ S-scheme heterojunction achieved approximately 89% chlortetracycline degradation after 180 min, while TOC decreased from 83% to only 29% of its initial value, again demonstrating that significant quantities of partially oxidized organic products persisted after removal of the parent antibiotic [128]. These representative examples emphasize that TOC analysis is indispensable for distinguishing pollutant degradation from true mineralization.

Beyond mineralization, the environmental safety of degradation intermediates has emerged as an equally important consideration. Several studies have demonstrated that partially oxidized products may exhibit higher toxicity than the parent antibiotic because structural modifications can enhance bioavailability or generate more reactive functional groups [133,134]. Consequently, recent work increasingly combines LC-MS identification of intermediates with computational and experimental toxicity assessment.

Currently, computational quantitative structure-activity relationship (QSAR) tools, particularly ECOSAR and the Toxicity Estimation Software Tool (T.E.S.T.), represent the most widely adopted first-line approach for evaluating transformation products [135]. Using the molecular structures identified by LC-MS, these programs estimate acute and chronic aquatic toxicity, developmental toxicity, mutagenicity, and bioaccumulation potential without requiring additional experimentation [136]. Several studies employing peroxymonosulfate activation and advanced oxidation processes have shown that certain hydroxylated or ring-opened intermediates were predicted by ECOSAR to exhibit toxicity toward algae and fish exceeding that of the parent antibiotic, with chronic toxicity for some tetracycline-derived intermediates increasing by more than three orders of magnitude [137–139]. In contrast, many porphyrin-MOF photocatalysts dominated by singlet oxygen generate intermediates predicted to possess lower bioaccumulation potential and reduced developmental toxicity, although isolated products may still remain environmentally relevant [75].

At the same time, recent literature demonstrates a clear shift toward validating these computational predictions through biological assays. Among these, *Vibrio fischeri* luminescent bacteria tests have become the most common rapid screening method for evaluating toxicity evolution during photocatalytic treatment [140]. Several studies reported increased luminescence inhibition during intermediate stages of tetracycline degradation, indicating transient formation of products more toxic than the parent compound [141]. More recently, *Danio rerio* (zebrafish) embryo assays have gained increasing attention because they evaluate developmental toxicity, hatching success, morphological abnormalities, and behavioral responses at the organism level [142]. In UV/H₂O₂/Fe(II) Fenton systems, zebrafish assays demonstrated that prolonged treatment substantially reduced acute toxic-

ity only after LC-MS confirmed extensive degradation and TOC measurements indicated progression toward mineralization, highlighting that detoxification frequently lags behind parent compound removal [143].

Overall, the current literature suggests that toxicity assessment is no longer based exclusively on computational prediction or biological testing. Instead, an integrated workflow is emerging in which LC-MS elucidates degradation pathways, QSAR tools such as ECOSAR or T.E.S.T. rapidly prioritize potentially hazardous intermediates, and *in vitro* bioassays provide experimental validation of ecological safety [144–146]. This combined approach represents the emerging standard of rigor for evaluating photocatalytic antibiotic degradation. Future studies on porphyrin-based MOFs should therefore routinely combine degradation efficiency, LC-MS pathway analysis, TOC mineralization measurements, and complementary toxicity assessment to distinguish simple pollutant removal from genuine environmental detoxification.

6. Challenges and Limitations of Por-MOFs

Despite the impressive efficiencies reported for Por-MOFs, several barriers still prevent direct translation into real wastewater treatment. First, many studies are performed under controlled laboratory conditions using single pollutants, whereas real water matrices contain competing ions, natural organic matter, mixed antibiotic cocktails, and variable pH, all of which can suppress adsorption or quench reactive oxygen species [147]. This is particularly relevant for defect-sensitive and charge-transfer-driven systems, whose performance may be more vulnerable to matrix effects than the headline values suggest. Therefore, future studies should place greater emphasis on realistic water conditions and mixed-contaminant scenarios [148]. Most MOFs, including porphyrinic variants, are electrically insulating due to the localized nature of their electronic states. This results in inefficient long-range electron transport and rapid recombination of photo-generated electron-hole pairs, which significantly reduces photocatalytic efficiency. Although strategies such as conductive linkers or metal-metal interactions have been explored, achieving intrinsically high conductivity remains challenging.

Catalyst stability and recyclability are also major concerns. Although some systems show good short-term reuse, long-term structural integrity, metal leaching, and retention of active sites remain insufficiently documented across the literature [149]. Many Por-MOFs exhibit limited hydrolytic, thermal, or photochemical stability, particularly under harsh operational conditions. Another concern is the photostability of porphyrins, which are susceptible to photodegradation (or photobleaching) under extended light exposure [150,151]. This is critical for Zr-, Hf-, and Fe-based materials, where structural robustness and catalytic cycling can differ significantly depending on synthesis route and surface chemistry. In addition, the move toward more complex heterostructures, dual-ligand frameworks, and multifunctional composites raises questions about synthetic reproducibility and scalability. A catalyst that performs exceptionally well on paper may still be impractical if its synthesis is multi-step, expensive, or difficult to scale [147]. In addition, slight variations in the synthesis of Por-MOFs may lead to differences in crystal size, defect density, and morphology, all of which influence catalytic performance.

One important concern is the cost of production. The synthesis of porphyrin ligands typically requires complex synthetic routes and labor-intensive purification steps, in addition to costly starting materials, which significantly limit their broader application. Since MOFs are constructed from metal nodes and organic linkers, careful selection of biocompatible or low-toxicity building blocks is essential to ensure safe use and with a lower environmental impact [152]. Moreover, the use of non-toxic or low-toxicity metal

ions such as Zr, Fe, Zn, Ca, and Mg enhances biocompatibility and minimizes potential adverse effects in the environment.

Finally, there is a need to bridge the gap between mechanistic understanding and engineering application. While significant progress has been made in elucidating ROS generation pathways and charge transfer mechanisms, these insights must be translated into practical reactor designs, including solar-driven systems and membrane-integrated technologies. Many of the most promising systems generate $1O_2$ or rely on efficient interfacial charge transfer, but these properties must eventually be integrated into immobilized or continuous-flow formats if the materials are to be used in practical treatment technologies [153]. Techniques like J-type π -stacking configuration demonstrate that aggregated porphyrin scored approximately four times higher performance in oxidizing thioanisole to sulfoxide compared to homogeneous TCPP. This is a key strategy for prolonged and sustainable ROS generation that improves photocatalytic oxidation via modulation of porphyrin aggregation [154].

7. AI-Guided Development of Photocatalysts for Efficient Antibiotic Degradation

The emergence of artificial intelligence and data-driven material discovery offers exciting opportunities for accelerating the design and optimization of next-generation Por-MOF photocatalysts. Machine learning approaches can facilitate the prediction of structure-property relationships, guide the rational selection of metal nodes and ligands, and assist in evaluating photocatalytic performance and degradation-product toxicity. As illustrated in Figure 12, AI-driven workflows significantly accelerate the discovery process by replacing labor-intensive experimental trial-and-error approaches with rapid, data-driven predictions.

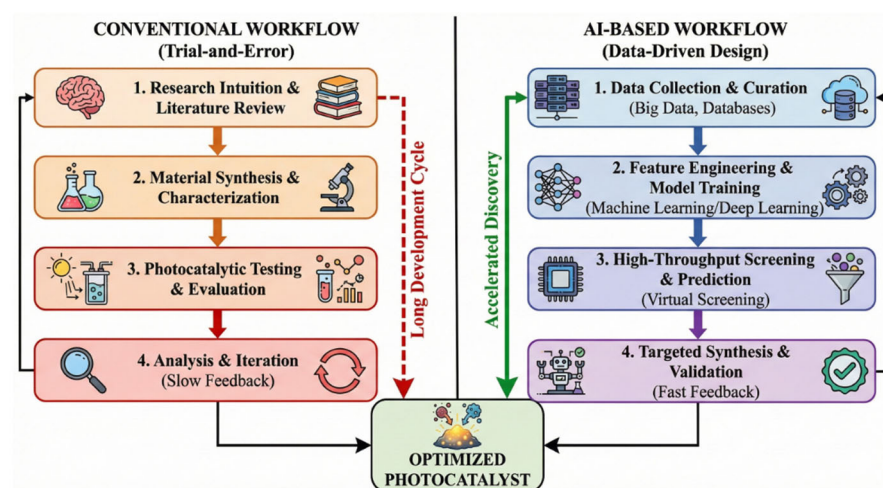


Figure 12. Schematic comparison between the conventional trial-and-error workflow (left) and the AI-based data-driven workflow (right) for the design and optimization of photocatalysts, produced from ref [155].

ML models have been used to design new photocatalysts [156]. The process begins with data collection from experimental databases and computational studies, followed by the generation and selection of relevant mathematical descriptors that encode material properties (Figure 13). These descriptors are subsequently used to select appropriate machine learning algorithms, develop predictive models, and establish robust structure-property relationships. Model training and validation are then performed to assess predictive accuracy [157].

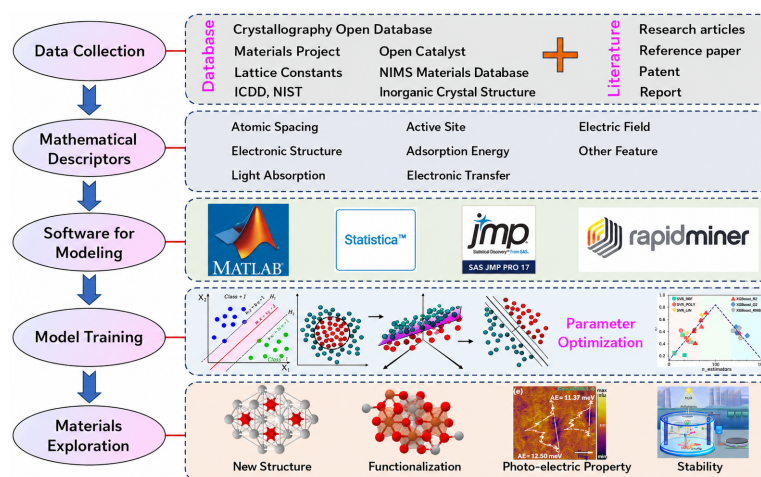


Figure 13. Procedures of AI for the selection and prediction of photocatalysts, produced from ref [157].

AI-based strategies are now recognized to offer three key advantages [155]. First, they enable high-throughput virtual screening of potential photocatalysts, allowing promising candidates to be identified before undertaking expensive and time-consuming synthesis and testing procedures. Second, they provide valuable mechanistic insights by establishing relationships between catalyst structure, often uncovering critical descriptors such as bandgap energy, surface defect density, and functional group distribution, the prediction of long-term photocatalyst stability, the optimization of synthesis parameters and photocatalytic performance. Third, AI models can predict the evolution of toxicity during degradation processes, thereby ensuring not only high degradation efficiency but also environmental safety.

Therefore, machine learning has enabled the multi-objective optimization of photocatalytic systems by simultaneously balancing degradation efficiency, catalyst stability, and energy consumption, thereby facilitating their practical implementation. By integrating advanced materials engineering, mechanistic understanding, and computational design tools, future Por-MOF research is expected to move toward highly efficient, sustainable, and application-oriented remediation technologies.

8. Future Perspectives

Recent advances have expanded the scope of Por-MOFs beyond conventional photocatalysis toward multifunctional systems incorporating defect engineering, heterojunction construction, photo-Fenton pathways, and synergistic adsorption-photocatalysis mechanisms. These developments reflect a broader transition from simple photocatalytic materials to rationally engineered platforms capable of selective pollutant degradation, improved catalytic efficiency, and operation under environmentally relevant conditions. Despite these significant achievements, several challenges continue to hinder the practical implementation of Por-MOFs in large-scale water treatment technologies. Long-term structural stability, photocorrosion, porphyrin photobleaching, catalyst recovery and reuse, framework scalability, and the limited evaluation of performance in complex wastewater matrices remain important concerns.

TCPP is one of the most widely used ligands for the synthesis of Por-MOFs due to its excellent versatility and favorable photophysical properties [158]. Researchers are also trying other porphyrin ligands to build Por-MOFs. Even if Por-MOFs made from these alternative ligands may have some performance drawbacks compared to TCPP-based systems, they can potentially be compensated using a strategy where different ligands are combined in the same framework. This approach may lead to the development of Por-MOFs with higher degradation efficiency.

The progression of photocatalytic technology toward industrial-scale commercialization is contingent upon the design and implementation of highly efficient photoreactors. Among the various advanced reactor configurations, the photocatalytic membrane reactor (PMR) has emerged as a particularly innovative technology [30]. This system synergistically integrates photocatalysis and membrane separation within a single unit, a design conceived to address the critical challenges of catalyst recovery and the management of photodecomposition products. Within this integrated framework, the photocatalytic component facilitates the mineralization of organic pollutants into benign substances, such as carbon dioxide and water. Concurrently, the membrane module serves a dual purpose: it acts as a physical barrier for the complete retention of the photocatalyst, enabling its recovery and reuse, and as a selective filter for the treated effluent [71]. Attributable to its high efficiency, operational simplicity, and inherently sustainable design, the PMR exhibits considerable promise as a viable and advanced technology for water and wastewater treatment [58]. Therefore, the design and development of efficient PMRs have emerged as a focal area of research, garnering significant attention in the field.

Another important point is the scaling of the MOFs synthesis using cost-effective and eco-friendly methods, which could help in the practical implementation of the MOFs for environmental applications. Researchers are actively investigating novel and scalable continuous synthesis strategies to enable the cost-effective production of high-quality MOFs. For certain MOF systems, methods such as electrochemical synthesis, microwave-assisted synthesis, and ultrasonic irradiation need to be integrated with continuous-flow reactors to facilitate large-scale manufacturing. However, to date, only a limited number of continuous-flow approaches have been successfully implemented for MOF production. Also, mechanochemical or solvent-free synthesis could reduce the environmental impact of the MOF production, which can be sustainable.

Under this perspective, industrial implementation currently requires available raw materials, simplified synthetic procedures, high production yields, and manufacturing processes alongside products of selective applications. Traditional photocatalysts (e.g., TiO_2 and $\text{g-C}_3\text{N}_4$), which have been widely used, benefit from low raw material costs, high availability and scalable synthesis procedures. However, they often suffer from limited optical response and low solar energy utilization, rapid charge recombination, weak oxidation of holes, limited specific area, without the possibility of further modification or sensitization [159]. In this context, the exceptional structural tunability of Por-MOFs, the catalytic selectivity, broad light-harvesting, and their ability to form hybrid and composite materials provide opportunities to overcome these limitations and achieve superior photocatalytic performance. Future studies can explore new types of linkages, assembly units, and synthetic routes suitable for constructing environmentally friendly porphyrin-based materials with lower preparation cost, catalytic performance, life cycle and regeneration efficiency.

Moreover, studies have shown that MOFs are predominantly employed in powder form [160]. However, this morphology is not optimal for industrial applications, as the recovery and separation of fine MOF particles from aqueous media are often complicated. Consequently, there is growing interest in alternative MOF configurations, including their immobilization on pellets, beads, aerogels, monoliths, or thin-film coatings. For example, an effective and easy-to-scale method for immobilization of PCN-222 on ceramic porous materials, Al_2O_3 foam, has been developed for the first time to remove chlorophenols via combined adsorption and visible-light photocatalysis [161]. This study clearly demonstrates a promising strategy for the immobilization of other Por-MOFs for diverse photocatalytic applications.

Moreover, many studies focus primarily on pollutant removal efficiencies, while comparatively less attention has been devoted to the identification of degradation intermediates,

mineralization pathways, and the potential toxicity of transformation products. Particular attention should be given to the use of toxic organic solvents, metal ions and functional groups in the organic ligands used during the synthetic procedures, which may leach into treated water during aqueous applications [160]. Exposure to or ingestion of such solvents can lead to adverse health effects [162]. Furthermore, prolonged exposure of these composites to sunlight and environmental conditions may induce secondary by-products, potentially resulting in the release of harmful chemicals that pose risks to both ecosystems and human health. This risk highlights the need for continued research and development of MOF-based hybrid nanocomposites using green synthetic approaches with eco-friendly starting materials, thereby minimizing their environmental impact.

9. Conclusions

Por-MOFs have emerged as highly promising materials for antibiotic degradation and water purification, owing to their unique ability to integrate pollutant adsorption, visible-light harvesting, charge separation, and reactive oxygen species generation within a single platform. Recent studies have demonstrated that their photocatalytic performance is strongly governed by structure-function relationships, including metal-node identity, ligand design, framework topology, defect engineering, and heterojunction construction. Through the rational optimization of these parameters, Por-MOFs can achieve efficient pollutant preconcentration, enhanced charge-carrier separation, and improved ROS production, resulting in superior photocatalytic degradation of a wide range of antibiotic contaminants. Among the various systems reported, Zr- and Hf-based Por-MOFs have consistently exhibited excellent hydrolytic stability and robust photocatalytic performance. The strong coordination bonds formed between tetravalent metal nodes and carboxylate ligands confer remarkable resistance to hydrolysis, while the porphyrinic framework enables efficient visible-light absorption and ligand-to-cluster charge transfer. These characteristics promote prolonged charge-carrier lifetimes, enhanced ROS generation, and sustained catalytic activity under aqueous conditions. Furthermore, their high surface areas and tunable pore architectures facilitate the adsorption and preconcentration of antibiotic molecules through π - π interactions, hydrogen bonding, and electrostatic attraction, further enhancing degradation efficiency [45,57,58,60,108].

Por-MOFs represent one of the most versatile and promising classes of photocatalysts for antibiotic degradation. Their ultimate success, however, will depend not only on achieving high laboratory-scale efficiencies but also on demonstrating long-term stability, economic viability, environmental safety, and scalability under real-world operating conditions.

Overall, future research should therefore focus on the development of more durable and scalable Por-MOF architectures, particularly through immobilization strategies, continuous-flow reactor configurations, and solar-driven photocatalytic systems capable of long-term operation under realistic environmental conditions. Comprehensive investigations into degradation pathways, mineralization efficiency, and ecotoxicological impacts are also essential to ensure the environmental safety of these technologies [43,45,46,57–59,71].

Author Contributions: Conceptualization, K.L.; writing—original draft preparation, D.R.B., M.-C.K. and K.L.; writing—review and editing, D.R.B., M.-C.K. and K.L.; visualization, K.L.; supervision, K.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: During the preparation of this manuscript/study, the authors used ChatGPT (Version 5.5) for text editing (English editing). Figure 3 was prepared by ChatGPT by giving it the text from our search at WOS, and for Figures 5 and 6, ChatGPT was used. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Falagas, M.E.; Kontogiannis, D.S.; Ragias, D.; Kakoullis, S.A. Antibiotics for the Treatment of Patients with Metallo- β -Lactamase (MBL)-Producing Gram-Negative Bacterial Infections. *Antibiotics* **2025**, *14*, 894. [\[CrossRef\]](#)
2. Caneschi, A.; Bardhi, A.; Barbarossa, A.; Zaghini, A. The Use of Antibiotics and Antimicrobial Resistance in Veterinary Medicine, a Complex Phenomenon: A Narrative Review. *Antibiotics* **2023**, *12*, 487. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Mohammed, E.A.H.; Kovács, B.; Kuunya, R.; Mustafa, E.O.A.; Abbo, A.S.H.; Pál, K. Antibiotic Resistance in Aquaculture: Challenges, Trends Analysis, and Alternative Approaches. *Antibiotics* **2025**, *14*, 598. [\[CrossRef\]](#) [\[PubMed\]](#)
4. He, J. Antibiotics Pollution in Cropland and Crops: A Comprehensive Review. *Adv. Agrochem.* **2025**, *4*, 316–323. [\[CrossRef\]](#)
5. Verhaegen, M.; Bergot, T.; Liebana, E.; Stancanelli, G.; Streissl, F.; Mingeot-Leclercq, M.-P.; Mahillon, J.; Bragard, C. On the Use of Antibiotics to Control Plant Pathogenic Bacteria: A Genetic and Genomic Perspective. *Front. Microbiol.* **2023**, *14*, 1221478. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Maghsodian, Z.; Sanati, A.M.; Mashifana, T.; Sillanpää, M.; Feng, S.; Nhat, T.; Ramavandi, B. Occurrence and Distribution of Antibiotics in the Water, Sediment, and Biota of Freshwater and Marine Environments: A Review. *Antibiotics* **2022**, *11*, 1461. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Sosa-Hernández, J.E.; Rodas-Zuluaga, L.I.; López-Pacheco, I.Y.; Melchor-Martínez, E.M.; Aghalari, Z.; Limón, D.S.; Iqbal, H.M.N.; Parra-Saldívar, R. Sources of Antibiotics Pollutants in the Aquatic Environment under SARS-CoV-2 Pandemic Situation. *Case Stud. Chem. Environ. Eng.* **2021**, *4*, 100127. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Polianciuc, S.I.; Gurzău, A.E.; Kiss, B.; Ștefan, M.G.; Loghin, F. Antibiotics in the Environment: Causes and Consequences. *Med. Pharm. Rep.* **2020**, *93*, 231–240. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Thakur, R.; Singh, A.; Dhanwar, R.; Kadam, S.; Waghmare, U.; Lodha, T.; Lopes, B.S.; Prakash, O. Global Perspectives on Residual Antibiotics: Environmental Challenges and Trends. *Discov. Sustain.* **2025**, *6*, 232. [\[CrossRef\]](#)
10. Izah, S.C.; Nurmahanova, A.; Ogwu, M.C.; Toktarbay, Z.; Umirbayeva, Z.; Ussen, K.; Koibasova, L.; Nazarbekova, S.; Tynybekov, B.; Guo, Z. Public Health Risks Associated with Antibiotic Residues in Poultry Food Products. *J. Agric. Food Res.* **2025**, *21*, 101815. [\[CrossRef\]](#)
11. Kweon, J.; Lee, H.; Kim, S.; Song, G. Environmental Antibiotic Emissions and Their Residual Impact on Livestock Farming. *Mol. Cell. Toxicol.* **2025**, *21*, 351–362. [\[CrossRef\]](#)
12. Mesfin, Y.M.; Mitiku, B.A.; Tamrat Admasu, H. Veterinary Drug Residues in Food Products of Animal Origin and Their Public Health Consequences: A Review. *Vet. Med. Sci.* **2024**, *10*, e70049. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Kiskó, G.; Bajramović, B.; Elzhraa, F.; Erdei-Tombor, P.; Dobó, V.; Mohácsi-Farkas, C.; Taczman-Brückner, A.; Belák, Á. The Invisible Threat of Antibiotic Resistance in Food. *Antibiotics* **2025**, *14*, 250. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Sharma, V.; Najar, I.N.; Radha, A.; Sharma, S.; Kumar, S.; Singh, D.; Gandhi, S.G.; Kumar, V. Advanced Integrated Eco-Strategies for Effective Antibiotic Waste Management. *Biodegradation* **2026**, *37*, 2. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Ji, J.; Li, H.; Liu, S. Current Natural Degradation and Artificial Intervention Removal Techniques for Antibiotics in the Aquatic Environment: A Review. *Appl. Sci.* **2025**, *15*, 5182. [\[CrossRef\]](#)
16. Zhang, S.; Zhang, X.; Shen, X.; Lu, X.; Guo, Y.; Li, Y.; Han, X.; Liu, R.; Chen, F.; Sun, C. Research Status of Membrane Separation Technology in the Treatment of Antibiotic Wastewater. *Environ. Sci. Water Res. Technol.* **2025**, *11*, 1386–1400. [\[CrossRef\]](#)
17. Majidian, S.; Tavakoly Sany, S.B.; Esrafil, A. A Systematic Review on Application of Photocatalytic Degradation Using COFs in the Reduction of Tetracycline from Wastewater. *Desalin. Water Treat.* **2026**, *325*, 101692. [\[CrossRef\]](#)
18. Gao, Z.; Tan, J.; Khan, M.F.; Chugh, G.; Schmidt, O.; Ma, L.; Bu, D. Emerging Microbial and Enzymatic Approaches for Sustainable Antibiotic Biodegradation in Livestock Manure to Mitigate Water Pollution Risks. *Water* **2025**, *17*, 2960. [\[CrossRef\]](#)
19. Feng, Q.; Guo, K.; Liu, B.; Wang, C.; Yan, B.; Yue, Q.; Gao, Y.; Gao, B. Recent Advances and Prospects in Antibiotics Removal by Coagulation Technique: A Systematic Review. *J. Clean. Prod.* **2025**, *514*, 145825. [\[CrossRef\]](#)
20. Kurt, A.; Mert, B.K.; Özençin, N.; Sivrioğlu, Ö.; Yonar, T. Treatment of Antibiotics in Wastewater Using Advanced Oxidation Processes (AOPs). In *Physico-Chemical Wastewater Treatment and Resource Recovery*; Farooq, R., Ahmad, Z., Eds.; InTech: Hong Kong, China, 2017; ISBN 978-953-51-3129-8.

21. BK, V.; TR, S. Monitoring Antibiotic Pollutants in Water Using Electrochemical Techniques: A Detailed Review. *Crit. Rev. Anal. Chem.* **2026**, *56*, 103–132. [[CrossRef](#)] [[PubMed](#)]
22. Islam, M.; Khan, Z.U.H.; Islam, A.; Khasim, S.; Ahmad, F.; Ahmad, N.; Alsayer, I.A. Smart Adsorbent Frameworks Enabling High-Efficiency Pharmaceutical Degradation via Adsorption. *RSC Adv.* **2026**, *16*, 14688–14727. [[CrossRef](#)] [[PubMed](#)]
23. El-Sawaf, A.K.; Nassar, A.A.; Mubarak, M.F.; Hemdan, M. Nanoarchitectonics of Metal–Organic Framework Technologies for Dual Antibiotic Adsorption and Photocatalytic Degradation in Water Treatment. *J. Inorg. Organomet. Polym.* **2026**. [[CrossRef](#)]
24. Yao, B.; Yuan, J.; Yue, T.; Yu, S.; Xiao, S. Mechanism Optimization and Research Progress of MOFs-Based Photocatalysts in Antibiotic Degradation. *J. Alloys Compd.* **2025**, *1039*, 182955. [[CrossRef](#)]
25. Javed, M.S.; Nazir, M.A.; Shafiq, Z.; Ullah, S.; Najam, T.; Iqbal, R.; Ismail, M.A.; Tamang, T.L.; Shah, S.S.A. Advanced Materials for Photocatalytic Removal of Antibiotics from Wastewater. *J. Alloys Compd.* **2025**, *1010*, 177926. [[CrossRef](#)]
26. Al Miad, A.; Saikat, S.P.; Alam, M.K.; Sahadat Hossain, M.; Bahadur, N.M.; Ahmed, S. Metal Oxide-Based Photocatalysts for the Efficient Degradation of Organic Pollutants for a Sustainable Environment: A Review. *Nanoscale Adv.* **2024**, *6*, 4781–4803. [[CrossRef](#)] [[PubMed](#)]
27. Wang, W.; Ke, X. Photocatalytic Degradation of Antibiotics Using TiO₂/MOFs Nanocomposites: A Review. *Water Sci. Eng.* **2026**, *19*, 250–256. [[CrossRef](#)]
28. Qin, K.; Zhao, Q.; Yu, H.; Xia, X.; Li, J.; He, S.; Wei, L.; An, T. A Review of Bismuth-Based Photocatalysts for Antibiotic Degradation: Insight into the Photocatalytic Degradation Performance, Pathways and Relevant Mechanisms. *Environ. Res.* **2021**, *199*, 111360. [[CrossRef](#)] [[PubMed](#)]
29. Bineta, I.; Kirmani, O. A Review of G-C₃N₄-Based Photocatalysts for Antibiotic Elimination: Mechanistic Insights and Operational Parameters. *Chin. J. Anal. Chem.* **2026**, *54*, 100626. [[CrossRef](#)]
30. Akbari, M.; Rasouli, J.; Rasouli, K.; Ghaedi, S.; Mohammadi, M.; Rajabi, H.; Sabbaghi, S. MXene-Based Composite Photocatalysts for Efficient Degradation of Antibiotics in Wastewater. *Sci. Rep.* **2024**, *14*, 31498. [[CrossRef](#)] [[PubMed](#)]
31. Lykos, C.; Drivas, C.; Isaacs, M.A.; Ladomenou, K.; Kyzas, G.Z.; Albanis, T.; Konstantinou, I. Fabrication of 1D/2D WO₃ nanorods@Ti₃C₂T_x Schottky Junctions for Photocatalytic Removal of the Insecticide Clothianidin from Aqueous Matrices. *Mol. Catal.* **2026**, *590*, 115656. [[CrossRef](#)]
32. Chen, P.; Yan, M.; Shi, J.; Feng, M.; Li, Q.; Chen, H.; Xie, Y.; Lei, J.; Wakeel, M.; Hu, B.; et al. Applications of COFs and Their Derivatives in Photocatalysis for Energy Production and Harmful Substance Degradation. *Chem. Eur. J.* **2025**, *31*, e202500305. [[CrossRef](#)] [[PubMed](#)]
33. Asad, M.; Wang, S.; Wang, Q.-Y.; Li, L.-K.; Anwar, M.I.; Younas, A.; Zang, S.-Q. Aqueous Media Ultra-Sensitive Detection of Antibiotics via Highly Stable Luminescent 3D Cadmium-Based MOF. *New J. Chem.* **2021**, *45*, 20887–20894. [[CrossRef](#)]
34. Mohan, B.; Kumari, R.; Virender; Singh, G.; Singh, K.; Pombeiro, A.J.L.; Yang, X.; Ren, P. Covalent Organic Frameworks (COFs) and Metal–Organic Frameworks (MOFs) as Electrochemical Sensors for the Efficient Detection of Pharmaceutical Residues. *Environ. Int.* **2023**, *175*, 107928. [[CrossRef](#)] [[PubMed](#)]
35. Russo, V.; Hmoudah, M.; Broccoli, F.; Iesce, M.R.; Jung, O.-S.; Di Serio, M. Applications of Metal Organic Frameworks in Wastewater Treatment: A Review on Adsorption and Photodegradation. *Front. Chem. Eng.* **2020**, *2*, 581487. [[CrossRef](#)]
36. Alsehlhi, B.R. Toward Sustainable Environmental Cleanup: Metal–Organic Frameworks in Adsorption—A Review. *Desalin. Water Treat.* **2023**, *316*, 44–70. [[CrossRef](#)]
37. Virender, V.; Pandey, V.; Kumar, A.; Raghav, N.; Bhatia, P.; Pombeiro, A.J.L.; Singh, G.; Mohan, B. Tactical Metal–Organic Frameworks (MOFs) Adsorbent Advantages in Removal Applications. *Env. Sci. Pollut. Res.* **2025**, *32*, 6380–6404. [[CrossRef](#)] [[PubMed](#)]
38. Mohammed Ameen, S.S.; Omer, K.M.; Bedair, A.; Hamed, M.; Mansour, F.R. Recent Advances of Metal–Organic Frameworks as Nanozymes for Mercury Ions Detection in Environmental Samples. *Mater. Today Chem.* **2025**, *45*, 102686. [[CrossRef](#)]
39. Abonyi, M.N.; Obi, C.C.; Nwabanne, J.T. Degradation of Organic Pollutants in Wastewater Using MOF-Based Catalysts: A Review. *Next Mater.* **2025**, *8*, 100696. [[CrossRef](#)]
40. Dar, U.A.; Shah Nawaz, M.; Gupta, P. (Eds.) Front Matter. In *Porphyrin-Based Composites*; Wiley: Hoboken, NJ, USA, 2025; ISBN 978-1-394-21438-9.
41. Charisiadis, A.; Nikolaou, V.; Nikoloudakis, E.; Ladomenou, K.; Charalambidis, G.; Coutsolelos, A.G. Metalloporphyrins in Bio-Inspired Photocatalytic Conversions. *Chem. Commun.* **2025**, *61*, 4630–4646. [[CrossRef](#)] [[PubMed](#)]
42. Nikolaou, V.; Nikoloudakis, E.; Ladomenou, K.; Charalambidis, G.; Coutsolelos, A.G. Porphyrins—Valuable Pigments of Life. *Front. Chem. Biol.* **2024**, *2*, 1346465. [[CrossRef](#)]
43. Shee, N.K.; Kim, H.-J. Recent Developments in Porphyrin-Based Metal–Organic Framework Materials for Water Remediation under Visible-Light Irradiation. *IJMS* **2024**, *25*, 4183. [[CrossRef](#)] [[PubMed](#)]
44. Charisiadis, A.; Nikolaou, V.; Karikis, K.; Giatagana, C.; Chalepli, K.; Ladomenou, K.; Biswas, S.; Sharma, G.D.; Coutsolelos, A.G. Two New Bulky Substituted Zn Porphyrins Bearing Carboxylate Anchoring Groups as Promising Dyes for DSSCs. *New J. Chem.* **2016**, *40*, 5930–5941. [[CrossRef](#)]

45. Liu, F.; Rincón, I.; Baldoví, H.G.; Dhakshinamoorthy, A.; Horcajada, P.; Rojas, S.; Navalón, S.; Fateeva, A. Porphyrin-Based MOFs for Photocatalysis in Water: Advancements in Solar Fuels Generation and Pollutants Degradation. *Inorg. Chem. Front.* **2024**, *11*, 2212–2245. [\[CrossRef\]](#)
46. Tang, C.; Li, X.; Hu, Y.; Du, X.; Wang, S.; Chen, B.; Wang, S. Porphyrin-Based Metal–Organic Framework Materials: Design, Construction, and Application in the Field of Photocatalysis. *Molecules* **2024**, *29*, 467. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Kafentzi, M.-C.; Papageorgiou, G.; Ladomenou, K. From Porphyrinic MOFs and COFs to Hybrid Architectures: Design Principles for Photocatalytic H₂ Evolution. *Inorganics* **2026**, *14*, 32. [\[CrossRef\]](#)
48. Bitsos, D.R.; Salepis, A.; Orfanos, E.; Coutsolelos, A.G.; Kosheleva, R.I.; Mitropoulos, A.C.; Ladomenou, K. Exploring Metal- and Porphyrin-Modified TiO₂-Based Photocatalysts for Efficient and Sustainable Hydrogen Production. *Inorganics* **2025**, *13*, 121. [\[CrossRef\]](#)
49. Wu, H.; Liu, R.; Li, D.; Ng, Y.H. Porphyrin-Based Metal–Organic Frameworks for Photocatalytic Carbon Dioxide Reduction: Current Understanding and Challenges. *Nano Mater. Sci.* **2026**, *8*, 183–206. [\[CrossRef\]](#)
50. Ding, G.; Li, C.; Chen, L.; Liao, G. Porphyrin-Based Metal–Organic Frameworks for Photo(Electro)Catalytic CO₂ Reduction. *Energy Environ. Sci.* **2024**, *17*, 5311–5335. [\[CrossRef\]](#)
51. Gkika, D.A.; Ladomenou, K.; Bououdina, M.; Mitropoulos, A.C.; Kyzas, G.Z. Adsorption and Photocatalytic Applications of Porphyrin-Based Materials for Environmental Separation Processes: A Review. *Sci. Total Environ.* **2024**, *908*, 168293. [\[CrossRef\]](#) [\[PubMed\]](#)
52. Tsamtzidou, C.-K.; Theodoridis, A.; Bitsos, D.R.; Chalaris, M.; Ladomenou, K.; Nannou, C. Metalloporphyrin-Based Hybrid Photocatalyst for Bisphenol A Degradation: Kinetics, HRMS-Based Analysis of Transformation Products, and Toxicity Assessment. *RSC Adv.* **2026**, *16*, 18374–18388. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Rayati, S.; Jami, M.A.; Ghasemi, J.B. A Selective Fluorescent Sensor for Cu(II) Ion Based on Porphyrins Supported onto Multiwall Carbon Nanotubes. *Inorg. Chem. Commun.* **2025**, *180*, 114998. [\[CrossRef\]](#)
54. Bitsos, D.R.; Ofrydopoulou, A.; Tsoupras, A.; Charalambidis, G.; Coutsolelos, A.G.; Ladomenou, K. Photodynamic Therapy with Porphyrins for Skin Wound Healing and Infection Control. *J. Porphyr. Phthalocyanines* **2026**, *30*, 169–184. [\[CrossRef\]](#)
55. Tsoupras, A.; Pafli, S.; Stylianoudakis, C.; Ladomenou, K.; Demopoulos, C.A.; Philippopoulos, A. Anti-Inflammatory and Antithrombotic Potential of Metal-Based Complexes and Porphyrins. *Compounds* **2024**, *4*, 376–400. [\[CrossRef\]](#)
56. Rana, G.; Dhiman, P.; Kumar, A.; Wang, T.; Sharma, G. Recent Advances in Porphyrin-Based Metal Organic Frameworks and Composites for Photocatalytic Hydrogen Evolution and Water Treatment. *Chem. Eng. Res. Des.* **2023**, *199*, 620–638. [\[CrossRef\]](#)
57. Afreen, N.; Ahmad, N.; Kumar, G.; Anwer, A.H.; Benamor, A.; Coulon, F.; Ahmad, N. Porphyrin-Based Metal–Organic Frameworks as Sustainable Photocatalysts for Micropollutant Degradation: A Critical Review on Structure, Mechanism and Future Perspectives. *ACS EST. Water* **2025**, *5*, 2028–2040. [\[CrossRef\]](#)
58. Han, T.; Wang, S.; Salazar, G.A.; Rawashdeh-Omary, M. Porous Porphyrin-Based Photocatalysts: Recent Progress and Applications in Environmental Remediation. *Mater. Chem. Front.* **2026**, *10*, 164–183. [\[CrossRef\]](#)
59. Thakur, S.; Bharti, S. Recent Progress in Metal–Organic Frameworks Based Nanocomposites for Antibiotic Removal from Water: An in-Depth Review. *Environ. Sci. Pollut. Res.* **2025**, *33*, 5211–5241. [\[CrossRef\]](#) [\[PubMed\]](#)
60. Wang, Z.; Huang, J.; Wang, W.; Wang, X.; Wang, Y.; Gao, B.; Li, Q. Removal of Norfloxacin from High Salinity Wastewater by Hf-Porphyrin MOF with Missing Linker Defects: Insights into Anion Trapping and Photoinduced Charge Transfer Effects. *Chem. Eng. J.* **2023**, *466*, 143194. [\[CrossRef\]](#)
61. Phan, P.T.; Hong, J.; Tran, N.; Le, T.H. The Properties of Microwave-Assisted Synthesis of Metal–Organic Frameworks and Their Applications. *Nanomaterials* **2023**, *13*, 352. [\[CrossRef\]](#) [\[PubMed\]](#)
62. Yang, C.P.; Hu, C.Y.; Jiang, Z.W.; Xiao, S.Y.; Wang, X.Y.; Huang, C.Z.; Li, Y.F.; Zhen, S.J. Facile Synthesis of Porphyrin-MOFs with High Photo-Fenton Activity to Efficiently Degrade Ciprofloxacin. *J. Colloid. Interface Sci.* **2022**, *622*, 690–699. [\[CrossRef\]](#) [\[PubMed\]](#)
63. Letwaba, J.; Uyur, U.O.; Mavhungu, M.L.; Achuka, N.O.; Popoola, P.A. A Review on MOFs Synthesis and Effect of Their Structural Characteristics for Hydrogen Adsorption. *RSC Adv.* **2024**, *14*, 14233–14253. [\[CrossRef\]](#) [\[PubMed\]](#)
64. Ni, Z.; Masel, R.I. Rapid Production of Metal–Organic Frameworks via Microwave-Assisted Solvothermal Synthesis. *J. Am. Chem. Soc.* **2006**, *128*, 12394–12395. [\[CrossRef\]](#) [\[PubMed\]](#)
65. Thomas-Hillman, I.; Laybourn, A.; Dodds, C.; Kingman, S.W. Realising the Environmental Benefits of Metal–Organic Frameworks: Recent Advances in Microwave Synthesis. *J. Mater. Chem. A* **2018**, *6*, 11564–11581. [\[CrossRef\]](#)
66. Li, D.; Yadav, A.; Zhou, H.; Roy, K.; Thanasekaran, P.; Lee, C. Advances and Applications of Metal–Organic Frameworks (MOFs) in Emerging Technologies: A Comprehensive Review. *Glob. Chall.* **2024**, *8*, 2300244. [\[CrossRef\]](#) [\[PubMed\]](#)
67. Asad, M.; Anwar, M.I.; Miao, B.; Abbas, A.; Majeed, S.; Mir, I.A.; Rabbani, M.S.; Hussain, S.; Xu, S.; Al-Tahan, M.A.; et al. Recent Advances in Luminescent Metal–Organic Frameworks (L-MOFs) as Sustainable Materials for Sensing of Potentially Toxic Environmental Ubiquitous Explosive Contaminants. *Sustain. Mater. Technol.* **2024**, *42*, e01155. [\[CrossRef\]](#)

68. Rabeie, B.; Mahmoodi, N.M. Heterogeneous MIL-88A on MIL-88B Hybrid: A Promising Eco-Friendly Hybrid from Green Synthesis to Dual Application (Adsorption and Photocatalysis) in Tetracycline and Dyes Removal. *J. Colloid. Interface Sci.* **2024**, *654*, 495–522. [[CrossRef](#)] [[PubMed](#)]
69. Rabeie, B.; Mahmoodi, N.M. Green Synthesis of Biopolymer-Driven Dual Functional Carboxymethyl Cellulose Composite (CMC/MIL100(Fe)/MIL88A(Al)) as a Z-Scheme Photocatalyst and an Adsorbent for Water Pollutants. *Int. J. Biol. Macromol.* **2025**, *329*, 147358. [[CrossRef](#)] [[PubMed](#)]
70. Chen, F.-Z.; Li, Y.-J.; Zhou, M.; Gong, X.-X.; Gao, Y.; Cheng, G.; Ren, S.-B.; Han, D.-M. Smart Multifunctional Direct Z-Scheme In₂S₃@PCN-224 Heterojunction for Simultaneous Detection and Photodegradation towards Antibiotic Pollutants. *Appl. Catal. B Environ.* **2023**, *328*, 122517. [[CrossRef](#)]
71. Sutherland, C. Exploring the State-of-the-Art in Metal-Organic Frameworks for Antibiotic Adsorption: A Review of Performance, Mechanisms, and Regeneration. *Environ. Toxicol. Chem.* **2025**, *44*, 880–894. [[CrossRef](#)] [[PubMed](#)]
72. Wang, Z.; Li, M.; Li, J.; Zhou, W.; Wang, Y.; Li, Q. Sulfate Promotes the Photocatalytic Degradation of Antibiotics by Porphyrin MOF: The Electron-Donating Effect of the Anion. *Environ. Funct. Mater.* **2023**, *2*, 46–56. [[CrossRef](#)]
73. Zhu, Z.-H.; Li, Y.-L.; Wang, H.-L.; Zou, H.-H.; Liang, F.-P.; Zhou, L. Designing Pillar-Layered Metal–Organic Frameworks with Photo-Induced Electron Transfer Interactions between Ligands for Enhanced Photodynamic Sterilization and Photocatalytic Degradation of Dyes and Antibiotics. *J. Colloid. Interface Sci.* **2025**, *685*, 458–467. [[CrossRef](#)] [[PubMed](#)]
74. Guo, A.; Wang, X.; Liu, H.; Li, X.; Yang, L.; Yang, W. Efficient Photocatalytic Degradation of Water Contaminants via Ag Decorated Porphyrin-Based Organic Framework Materials. *Surf. Interfaces* **2023**, *38*, 102843. [[CrossRef](#)]
75. Yang, P.; Wu, C.; Zhang, X.; Sun, Q.; Hou, X.; Wang, T. Enhanced Photocatalytic Degradation of Sulfathiazole via Dual-Ligand Zr-MOFs: A Porphyrin and Pyrene-Based Energy Transfer. *Sep. Purif. Technol.* **2025**, *354*, 128727. [[CrossRef](#)]
76. Oyetade, J.A.; Iresemowo, O.A.; Adeoba, M.I.; Fayemi, O.E.; Abimbade, S.F.; Adeeyo, A.O. Functional Impacts of Carbon-Based Nanomaterials in the Performance of Heterostructure Photocatalysts for the Remediation of Pharmaceutical Pollutants in Wastewater—A Review. *Nano-Struct. Nano-Objects* **2026**, *46*, 101675. [[CrossRef](#)]
77. Ahmad, N.; Bano, D.; Jabeen, S.; Ahmad, N.; Iqbal, A.; Waris, Anwer, A.H.; Jeong, C. Insight into the Adsorption Thermodynamics, Kinetics, and Photocatalytic Studies of Polyaniline/SnS₂ Nanocomposite for Dye Removal. *J. Hazard. Mater. Adv.* **2023**, *10*, 100321. [[CrossRef](#)]
78. Quan, X.; Sun, Z.; Meng, H.; Han, Y.; Wu, J.; Xu, J.; Xu, Y.; Zhang, X. Polyethyleneimine (PEI) Incorporated Cu-BTC Composites: Extended Applications in Ultra-High Efficient Removal of Congo Red. *J. Solid. State Chem.* **2019**, *270*, 231–241. [[CrossRef](#)]
79. Haldar, R.; Ghosh, A.; Maji, T.K. Charge Transfer in Metal–Organic Frameworks. *Chem. Commun.* **2023**, *59*, 1569–1588. [[CrossRef](#)] [[PubMed](#)]
80. Rajasree, S.S.; Li, X.; Deria, P. Physical Properties of Porphyrin-Based Crystalline Metal–organic Frameworks. *Commun. Chem.* **2021**, *4*, 47. [[CrossRef](#)] [[PubMed](#)]
81. Li, N.; Ma, Y.; Sun, W. Exploring the Dynamics of Charge Transfer in Photocatalysis: Applications of Femtosecond Transient Absorption Spectroscopy. *Molecules* **2024**, *29*, 3995. [[CrossRef](#)] [[PubMed](#)]
82. Wang, Z.; Wang, C. Excited State Energy Transfer in Metal-Organic Frameworks. *Adv. Mater.* **2021**, *33*, 2005819. [[CrossRef](#)] [[PubMed](#)]
83. Shaikh, S.M.; Chakraborty, A.; Alatis, J.; Cai, M.; Danilov, E.; Morris, A.J. Light Harvesting and Energy Transfer in a Porphyrin-Based Metal Organic Framework. *Faraday Discuss.* **2019**, *216*, 174–190. [[CrossRef](#)] [[PubMed](#)]
84. Qi, C.; Luo, X.; Pan, H.; Wang, W.; Zheng, X. Biomedical Applications and Perspectives of Two-Dimensional Porphyrin-Based MOFs. *Front. Pharmacol.* **2026**, *17*, 1819283. [[CrossRef](#)] [[PubMed](#)]
85. Zhang, Y.; Yan, L.; Li, Y.; Si, J.; Tan, W.; Hou, X. Nonlinear Optical Limiting Effect and Charge Transfer Dynamics in a Fe-Porphyrin Metal-Organic Framework. *Opt. Mater. Express* **2023**, *13*, 484. [[CrossRef](#)]
86. Li, X.; Deria, P. Chapter 6. Light Harvesting in Porphyrin-Based Metal–Organic Frameworks. In *Monographs in Supramolecular Chemistry*; Ma, S., Verma, G., Eds.; Royal Society of Chemistry: Cambridge, UK, 2021; pp. 188–255, ISBN 978-1-83916-180-3.
87. Ortega-Guerrero, A.; Fumanal, M.; Capano, G.; Tavernelli, I.; Smit, B. Insights into the Electronic Properties and Charge Transfer Mechanism of a Porphyrin Ruthenium-Based Metal–Organic Framework. *Chem. Mater.* **2020**, *32*, 4194–4204. [[CrossRef](#)]
88. Arissa, A.; Rose, T.; Leick, N.; Grimme, S.; Johnson, J.C.; Lockard, J.V. Charge Transfer and Recombination Pathways through Fullerene Guests in Porphyrin-Based MOFs. *J. Phys. Chem. C* **2025**, *129*, 8215–8227. [[CrossRef](#)] [[PubMed](#)]
89. Li, X.; Yu, J.; Lu, Z.; Duan, J.; Fry, H.C.; Gosztola, D.J.; Maindan, K.; Rajasree, S.S.; Deria, P. Photoinduced Charge Transfer with a Small Driving Force Facilitated by Exciplex-like Complex Formation in Metal–Organic Frameworks. *J. Am. Chem. Soc.* **2021**, *143*, 15286–15297. [[CrossRef](#)] [[PubMed](#)]
90. Jin, H.-G.; Lin, W.; Zhao, P.-C.; Deng, J.; Liu, Y.; Gu, Z.-G.; Chao, Z.-S. Donor-Acceptor Mixed-Ligand MOF with Energy Transfer-Mediated High-Efficiency Singlet Oxygen Generation for Boosted Organic Photosynthesis. *J. Colloid. Interface Sci.* **2025**, *689*, 137231. [[CrossRef](#)] [[PubMed](#)]

91. Adams, M.; Kozłowska, M.; Baroni, N.; Oldenburg, M.; Ma, R.; Busko, D.; Turshatov, A.; Emandi, G.; Senge, M.O.; Haldar, R.; et al. Highly Efficient One-Dimensional Triplet Exciton Transport in a Palladium–Porphyrin-Based Surface-Anchored Metal–Organic Framework. *ACS Appl. Mater. Interfaces* **2019**, *11*, 15688–15697. [[CrossRef](#)] [[PubMed](#)]
92. Afrin, S.; Yang, X.; Morris, A.J.; Grumstrup, E.M. Rapid Exciton Transport and Structural Defects in Individual Porphyrinic Metal Organic Framework Microcrystals. *J. Am. Chem. Soc.* **2024**, *146*, 4309–4313. [[CrossRef](#)] [[PubMed](#)]
93. Ahmad, N.; Sultana, S.; Sabir, S.; Khan, M.Z. Exploring the Visible Light Driven Photocatalysis by Reduced Graphene Oxide Supported Ppy/CdS Nanocomposites for the Degradation of Organic Pollutants. *J. Photochem. Photobiol. A Chem.* **2020**, *386*, 112129. [[CrossRef](#)]
94. Banerjee, S.; Pillai, S.C.; Falaras, P.; O'Shea, K.E.; Byrne, J.A.; Dionysiou, D.D. New Insights into the Mechanism of Visible Light Photocatalysis. *J. Phys. Chem. Lett.* **2014**, *5*, 2543–2554. [[CrossRef](#)] [[PubMed](#)]
95. Dey, S.; Mondal, S.; Habib, M.; Sarkar, R.; Pal, S. Electron–Hole Recombination Is Suppressed by Breaking the Ring Planarity in Porphyrin Nanorings: Density Functional Atomistic Simulation. *J. Phys. Chem. C* **2025**, *129*, 6840–6849. [[CrossRef](#)]
96. Cheng, F.; Wang, J. Regulating Hydroxyl Radicals ($\bullet\text{OH}$) and Hydrated Electron (e_{aq}) for Enhanced Radiolytic Degradation of 4-Nitrophenol by Addition of H_2O_2 . *ACS EST. Water* **2024**, *4*, 5077–5088. [[CrossRef](#)]
97. Chakravorty, A.; Roy, S. A Review of Photocatalysis, Basic Principles, Processes, and Materials. *Sustain. Chem. Environ.* **2024**, *8*, 100155. [[CrossRef](#)]
98. Liu, C.; Liu, K.; Wang, C.; Liu, H.; Wang, H.; Su, H.; Li, X.; Chen, B.; Jiang, J. Elucidating Heterogeneous Photocatalytic Superiority of Microporous Porphyrin Organic Cage. *Nat. Commun.* **2020**, *11*, 1047. [[CrossRef](#)] [[PubMed](#)]
99. Shafi, A.; Ahmad, N.; Sultana, S.; Sabir, S.; Khan, M.Z. Ag₂S-Sensitized NiO–ZnO Heterostructures with Enhanced Visible Light Photocatalytic Activity and Acetone Sensing Property. *ACS Omega* **2019**, *4*, 12905–12918. [[CrossRef](#)] [[PubMed](#)]
100. Kumar, P.; Deep, A.; Kim, K.-H. Metal Organic Frameworks for Sensing Applications. *TrAC. Trends Anal. Chem.* **2015**, *73*, 39–53. [[CrossRef](#)]
101. Kabra, K.; Chaudhary, R.; Sawhney, R.L. Treatment of Hazardous Organic and Inorganic Compounds through Aqueous-Phase Photocatalysis: A Review. *Ind. Eng. Chem. Res.* **2004**, *43*, 7683–7696. [[CrossRef](#)]
102. Cycoń, M.; Mroziński, A.; Piotrowska-Seget, Z. Antibiotics in the Soil Environment—Degradation and Their Impact on Microbial Activity and Diversity. *Front. Microbiol.* **2019**, *10*, 338. [[CrossRef](#)] [[PubMed](#)]
103. Yang, Q.; Gao, Y.; Ke, J.; Show, P.L.; Ge, Y.; Liu, Y.; Guo, R.; Chen, J. Antibiotics: An Overview on the Environmental Occurrence, Toxicity, Degradation, and Removal Methods. *Bioengineered* **2021**, *12*, 7376–7416. [[CrossRef](#)] [[PubMed](#)]
104. Zhu, L.; Lin, X.; Di, Z.; Cheng, F.; Xu, J. Occurrence, Risks, and Removal Methods of Antibiotics in Urban Wastewater Treatment Systems: A Review. *Water* **2024**, *16*, 3428. [[CrossRef](#)]
105. Conde-Cid, M.; Núñez-Delgado, A.; Fernández-Sanjurjo, M.; Álvarez-Rodríguez, E.; Fernández-Calviño, D.; Arias-Estévez, M. Tetracycline and Sulfonamide Antibiotics in Soils: Presence, Fate and Environmental Risks. *Processes* **2020**, *8*, 1479. [[CrossRef](#)]
106. Scaria, J.; Anupama, K.V.; Nidheesh, P.V. Tetracyclines in the Environment: An Overview on the Occurrence, Fate, Toxicity, Detection, Removal Methods, and Sludge Management. *Sci. Total Environ.* **2021**, *771*, 145291. [[CrossRef](#)] [[PubMed](#)]
107. Semenova, Y.; Makalkina, L.; Glushkova, N.; Gaipov, A. Tetracyclines in the Modern Era: Global Consumption, Antimicrobial Resistance, Environmental Occurrence, and Degradation Techniques. *Antibiotics* **2025**, *14*, 1183. [[CrossRef](#)] [[PubMed](#)]
108. Zong, Y.; Ma, S.; Gao, J.; Xu, M.; Xue, J.; Wang, M. Synthesis of Porphyrin Zr-MOFs for the Adsorption and Photodegradation of Antibiotics under Visible Light. *ACS Omega* **2021**, *6*, 17228–17238. [[CrossRef](#)] [[PubMed](#)]
109. Pang, W.; Chen, R.; Wang, Y.; Jia, X.; Hou, J.; Wang, L.; Gao, Z.; Zhou, H. Organic Ligands Modulation of Ti-Based Hierarchical MOFs to Improve Visible-Light-Driven Catalytic Degradation Properties for Tetracycline Antibiotics. *Sep. Purif. Technol.* **2025**, *361*, 131600. [[CrossRef](#)]
110. Saxena, S.; Saluja, P.; Krishna, J.; Basu, T. Morphological and Structural Elucidation of Room Temperature Catalytic Degradation of Amoxicillin Antibiotic Using Zinc Porphyrin Metal Organic Framework. *Adv. Mater. Res.* **2021**, *10*, 23. [[CrossRef](#)]
111. Martell Mendoza, M.; Alberto Méndez Cuesta, C.; Angel Zavala Sánchez, M.; Cuauhtemoc Pérez Montiel, E.; Mata Bermúdez, A.; Pérez González, C. Metal Organic Frameworks Used as Antibiotic Removal Agents in Water. In *Wastewater Treatment and Sludge Management Systems—The Gutter-to-Good Approaches*; Kılıç Taşeli, B., Jacob-Lopes, E., Queiroz Zepka, L., Costa Deprá, M., Eds.; IntechOpen: London, UK, 2024; ISBN 978-0-85466-743-7.
112. Awfa, D.; Ateia, M.; Fujii, M.; Yoshimura, C. Photocatalytic Degradation of Organic Micropollutants: Inhibition Mechanisms by Different Fractions of Natural Organic Matter. *Water Res.* **2020**, *174*, 115643. [[CrossRef](#)] [[PubMed](#)]
113. Zheng, M.; Shao, Y.; Ma, F.; Li, W.; Guo, M. Adsorption of Antibiotics in Medical Wastewater by MOF-Based Hydrogel Composites: A Comprehensive Review. *J. Water Process Eng.* **2025**, *76*, 108268. [[CrossRef](#)]
114. Nishmitha, P.S.; Akhilghosh, K.A.; Aiswriya, V.P.; Ramesh, A.; Muthuchamy, M.; Muthukumar, A. Understanding Emerging Contaminants in Water and Wastewater: A Comprehensive Review on Detection, Impacts, and Solutions. *J. Hazard. Mater. Adv.* **2025**, *18*, 100755. [[CrossRef](#)]

115. Yakamercan, E.; Obijanya, C.C.; Jayakrishnan, U.; Aygun, A.; Velluru, S.; Karimi, M.; Terapalli, A.; Simsek, H. A Critical Review of Contaminants of Emerging Concern in Reclaimed Wastewater: Implications for Agricultural Irrigation. *Water Conserv. Sci. Eng.* **2025**, *10*, 112. [\[CrossRef\]](#)
116. Jurczynski, Y.; Passos, R.; Campos, L.C. A Review of the Most Concerning Chemical Contaminants in Drinking Water for Human Health. *Sustainability* **2024**, *16*, 7107. [\[CrossRef\]](#)
117. Kumar, R.; Qureshi, M.; Vishwakarma, D.K.; Al-Ansari, N.; Kuriqi, A.; Elbeltagi, A.; Saraswat, A. A Review on Emerging Water Contaminants and the Application of Sustainable Removal Technologies. *Case Stud. Chem. Environ. Eng.* **2022**, *6*, 100219. [\[CrossRef\]](#)
118. Gmelas, S.R.D.; Tomé, J.P.C.; Tomé, A.C.; Lourenço, L.M.O. Porphyrin-Containing Materials for Photodegradation of Organic Pollutants in Wastewaters: A Review. *Catal. Sci. Technol.* **2024**, *14*, 2352–2389. [\[CrossRef\]](#)
119. Zhao, C.; Pelaez, M.; Duan, X.; Deng, H.; O'Shea, K.; Fatta-Kassinos, D.; Dionysiou, D.D. Role of pH on Photolytic and Photocatalytic Degradation of Antibiotic Oxytetracycline in Aqueous Solution under Visible/Solar Light: Kinetics and Mechanism Studies. *Appl. Catal. B Environ.* **2013**, *134–135*, 83–92. [\[CrossRef\]](#)
120. Wenk, J.; Graf, C.; Aeschbacher, M.; Sander, M.; Canonica, S. Effect of Solution pH on the Dual Role of Dissolved Organic Matter in Sensitized Pollutant Photooxidation. *Environ. Sci. Technol.* **2021**, *55*, 15110–15122. [\[CrossRef\]](#) [\[PubMed\]](#)
121. Katiya, M.M.; Dhonde, M.G. Porphyrin-Based Photocatalysts for Organic Transformations: From Molecular Design to Sustainable Applications. *J. Photochem. Photobiol. A Chem.* **2026**, *480*, 117380. [\[CrossRef\]](#)
122. Hemmer, K.; Boström, H.L.B.; Krause, S.; Lotsch, B.V.; Fischer, R.A. Strategies to Achieve Reproducible Synthesis of Phase-Pure Zr-Porphyrin Metal-Organic Frameworks. *Commun. Mater.* **2024**, *5*, 264. [\[CrossRef\]](#)
123. Gan, X.; Li, X.; Wang, B. Adsorption and Degradation of Multiple Micropollutants with Trace Concentrations by Porous Zr-Porphyrin Metal-Organic Frameworks with Missing Linker Defects in Water. *Microporous Mesoporous Mater.* **2023**, *349*, 112444. [\[CrossRef\]](#)
124. Piccirillo, G.; Maldonado-Carmona, N.; Marques, D.L.; Villandier, N.; Calliste, C.A.; Leroy-Lhez, S.; Eusébio, M.E.S.; Calvete, M.J.F.; Pereira, M.M. Porphyrin@Lignin Nanoparticles: Reusable Photocatalysts for Effective Aqueous Degradation of Antibiotics. *Catal. Today* **2023**, *423*, 113903. [\[CrossRef\]](#)
125. Salahshournia, B.; Noroozi, A.; Fortin, D.; Shkreta, L.; Chabot, B.; Soldera, A.; Cabana, H.; Harvey, P.D. A Porphyrin-Based Metal–Organic Framework as a Photosensitizer for Singlet Oxygen Generation and Photocatalytic Water Treatment. *ACS Appl. Opt. Mater.* **2025**, *3*, 1254–1267. [\[CrossRef\]](#)
126. Zhao, S.; Li, S.; Zhao, Z.; Su, Y.; Long, Y.; Zheng, Z.; Cui, D.; Liu, Y.; Wang, C.; Zhang, X.; et al. Microwave-Assisted Hydrothermal Assembly of 2D Copper-Porphyrin Metal-Organic Frameworks for the Removal of Dyes and Antibiotics from Water. *Environ. Sci. Pollut. Res.* **2020**, *27*, 39186–39197. [\[CrossRef\]](#) [\[PubMed\]](#)
127. Duan, L.; Cheng, T.; Zhu, Y.; Wang, Y.; Gao, Y.; Bi, J. Lanthanide-Porphyrin MOF as a Multifunctional Platform for Detection and Integrated Elimination of Cr(VI) and Ciprofloxacin. *Inorg. Chem.* **2025**, *64*, 1983–1993. [\[CrossRef\]](#) [\[PubMed\]](#)
128. Huang, M.; Wang, Y.; Zhou, M.; Xu, S.; Li, Z.; Li, H. Visible-Light-Driven Photocatalytic Degradation of Chlortetracycline over PCN-222/Zn₃In₂S₆ Heterostructure: Elucidation of Degradation Mechanisms and Ecotoxicological Evaluation. *Results Surf. Interfaces* **2026**, *22*, 100721. [\[CrossRef\]](#)
129. Bai, X.; Zhang, W.; Tang, C.; Wang, Y.; Shen, Q.; Shao, S.; Liu, G.; Dong, S. Donor-Acceptor Photoelectrochemical Strategy for Efficient Detection and Degradation Chloramphenicol Based on Dual-Porphyrin Z-Scheme Heterostructure. *Biosens. Bioelectron.* **2026**, *291*, 118026. [\[CrossRef\]](#) [\[PubMed\]](#)
130. Hu, X.; Ji, F.; Liao, X.; Zhang, Z.; Ding, T. Mechanisms and Toxicity of Plasma-Induced Antibiotic Degradation: Advances in Synergistic Strategies and Computational Evaluation. *CyTA J. Food* **2025**, *23*, 2596439. [\[CrossRef\]](#)
131. Liu, H.; Qu, J.; Zhang, T.; Ren, M.; Zhang, Z.; Cheng, F.; He, D.; Zhang, Y. Insights into Degradation Pathways and Toxicity Changes during Electro-Catalytic Degradation of Tetracycline Hydrochloride. *Environ. Pollut.* **2020**, *258*, 113702. [\[CrossRef\]](#) [\[PubMed\]](#)
132. Han, H.; Huang, Z.; Wang, S.; Zhou, L.; Li, S.; Peng, X. Efficient Biotransformation of Norfloxacin by *Castellaniella Defragrans* HL-1: Kinetics, Pathways, Toxicity Assessment, and Genomic Insights. *J. Hazard. Mater.* **2025**, *495*, 138981. [\[CrossRef\]](#) [\[PubMed\]](#)
133. Wang, M.; Lu, G.; Jiang, R.; Dang, T.; Liu, J. Degradation and Detoxification of Broad-Spectrum Antibiotics by Small Molecular Intercalated BiOCl under Visible Light. *J. Colloid. Interface Sci.* **2022**, *622*, 995–1007. [\[CrossRef\]](#) [\[PubMed\]](#)
134. Li, M.; Ma, M.; Zhao, Z.; Bao, M.; Zhang, N.; Zhou, Y.; Zheng, Y. Simultaneous Degradation of Binary Fluoroquinolone Antibiotics by B and N In-Situ Self-Doped Guar Gum Hydrogel. *Chemosphere* **2023**, *342*, 140197. [\[CrossRef\]](#) [\[PubMed\]](#)
135. Massarsky, A.; Donnell, M.T.; De Gandiaga, E.; Kozal, J.S.; Garnick, L.; Kubitz, J.A.; Bartell, S.M.; Monnot, A.D. Critical Evaluation of ECOSAR and E-FAST Platforms to Predict Ecological Risks of PFAS. *Environ. Adv.* **2022**, *8*, 100221. [\[CrossRef\]](#)
136. Osin, O.A.; Yu, T.; Cai, X.; Jiang, Y.; Peng, G.; Cheng, X.; Li, R.; Qin, Y.; Lin, S. Photocatalytic Degradation of 4-Nitrophenol by C, N-TiO₂: Degradation Efficiency vs. Embryonic Toxicity of the Resulting Compounds. *Front. Chem.* **2018**, *6*, 192. [\[CrossRef\]](#) [\[PubMed\]](#)

137. Duarte, J.L.S.; Hayat, A.; Domínguez, C.M.; Santos, A.; Cotillas, S. Degradation Pathways and in Silico Ecotoxicity Assessment of Meropenem By-Products Generated by Electrochemical Oxidation. *J. Environ. Chem. Eng.* **2026**, *14*, 123814. [\[CrossRef\]](#)
138. Sun, S.; Wang, Z.; Pu, Q.; Li, X.; Cui, Y.; Yang, H.; Li, Y. Identification and Mechanistic Analysis of Toxic Degradation Products in the Advanced Oxidation Pathways of Fluoroquinolone Antibiotics. *Toxics* **2024**, *12*, 203. [\[CrossRef\]](#) [\[PubMed\]](#)
139. Sagir, D.; Ozen, I.; Arslan Cene, G.; Yazici Guvenc, S.; Can-Güven, E.; Varank, G.; Çifçi, D.İ. Investigation of Different Activation Methods in Peroxymonosulfate Oxidation for the Treatment of Chemical Industry Wastewater. *J. Environ. Chem. Eng.* **2025**, *13*, 119861. [\[CrossRef\]](#)
140. Ge, S.; Tian, W.; Lou, Z.; Wang, X.; Zhuang, L.-L.; Zhang, J. Long-Term Toxicity Assessment of Antibiotics against *Vibrio Fischeri*: Test Method Optimization and Mixture Toxicity Prediction. *J. Hazard. Mater.* **2024**, *469*, 133933. [\[CrossRef\]](#) [\[PubMed\]](#)
141. Jiao, S.; Zheng, S.; Yin, D.; Wang, L.; Chen, L. Aqueous Photolysis of Tetracycline and Toxicity of Photolytic Products to Luminescent Bacteria. *Chemosphere* **2008**, *73*, 377–382. [\[CrossRef\]](#) [\[PubMed\]](#)
142. Wang, H.; Che, B.; Duan, A.; Mao, J.; Dahlgren, R.A.; Zhang, M.; Zhang, H.; Zeng, A.; Wang, X. Toxicity Evaluation of B-diketone Antibiotics on the Development of Embryo-larval Zebrafish (*Danio Rerio*). *Environ. Toxicol.* **2014**, *29*, 1134–1146. [\[CrossRef\]](#) [\[PubMed\]](#)
143. Qiu, W.; Zheng, M.; Sun, J.; Tian, Y.; Fang, M.; Zheng, Y.; Zhang, T.; Zheng, C. Photolysis of Enrofloxacin, Pefloxacin and Sulfaquinoxaline in Aqueous Solution by UV/H₂O₂, UV/Fe(II), and UV/H₂O₂/Fe(II) and the Toxicity of the Final Reaction Solutions on Zebrafish Embryos. *Sci. Total Environ.* **2019**, *651*, 1457–1468. [\[CrossRef\]](#) [\[PubMed\]](#)
144. Ogwu, M.C.; Izah, S.C.; Aliu, O.O.; Kari, A.; Alum, E.U. Transformation Products of Emerging Contaminants and Their Formation Pathways, Environmental Fate, Predictive Modeling, and Regulatory Risk Implications. *Discov. Environ.* **2026**, *4*, 317. [\[CrossRef\]](#)
145. Singh, A.K.; Pandey, S.; Pal, S.; Ahmad, I.; Katari, S.K. Computational Framework as a Way Forward Robust Approach in Predictive Biodegradation and Underlying Toxic Hazards Assessment of Environmental Contaminants. *ChemistrySelect* **2025**, *10*, e01333. [\[CrossRef\]](#)
146. Boucetta, H.; Russell, P.; Rudd, D.; Jörg, M. From Lab to Environment: Forecasting Pharmaceutical Impact Using in Silico and Analytical Tools. *RSC Med. Chem.* **2026**, *17*, 768–783. [\[CrossRef\]](#) [\[PubMed\]](#)
147. Mussa, N.-S.; Toshtay, K.; Dumeignil, F. Recent Developments in the Field of MOF-Based Catalytic Systems: A Review. *Appl. Catal. A Gen.* **2025**, *708*, 120555. [\[CrossRef\]](#)
148. Moore, S.C.; Smith, M.R.; Trettin, J.L.; Yang, R.A.; Sarazen, M.L. Kinetic Impacts of Defect Sites in Metal–Organic Framework Catalysts under Varied Driving Forces. *ACS Energy Lett.* **2023**, *8*, 1397–1407. [\[CrossRef\]](#)
149. Liberman, I.; Shimoni, R.; Ifraemov, R.; Rozenberg, I.; Singh, C.; Hod, I. Active-Site Modulation in an Fe-Porphyrin-Based Metal–Organic Framework through Ligand Axial Coordination: Accelerating Electrocatalysis and Charge-Transport Kinetics. *J. Am. Chem. Soc.* **2020**, *142*, 1933–1940. [\[CrossRef\]](#) [\[PubMed\]](#)
150. Golec, B.; Buczyńska, J.; Nawara, K.; Gorski, A.; Waluk, J. Photodegradation of Free Base and Zinc Porphyrins in the Presence and Absence of Oxygen. *Photochem. Photobiol. Sci.* **2023**, *22*, 2725–2734. [\[CrossRef\]](#) [\[PubMed\]](#)
151. Hassan, G.F.; El Hoda Saad, N.; Hmadeh, M.; Karam, P. Enhancing Porphyrin Photostability When Locked in Metal–Organic Frameworks. *Dalton Trans.* **2018**, *47*, 15765–15771. [\[CrossRef\]](#) [\[PubMed\]](#)
152. Chen, J.; Zhu, Y.; Kaskel, S. Porphyrin-Based Metal–Organic Frameworks for Biomedical Applications. *Angew. Chem. Int. Ed.* **2021**, *60*, 5010–5035. [\[CrossRef\]](#) [\[PubMed\]](#)
153. Haider, S.A.; Sajjad, B.; Shahid, M.; Altaf, M.; Chotana, G.A.; Sohail, M.; Rasul, S.; Ashraf, R.S. Porphyrin-Based Metal–Organic Frameworks: Advanced Materials for the Oxygen Evolution Reaction. *J. Mol. Struct.* **2025**, *1348*, 143503. [\[CrossRef\]](#)
154. Zhong, H.-K.; Feng, J.-R.; Yu, H.-Y.; Wen, T.-T.; Gou, H.-W.; Zheng, S.-Y.; Liu, X.-H.; Xue, C.; Zhou, X.-T. Enhancing Photocatalytic Oxidation via Porphyrin Aggregation State Modulation for Boosted Reactive Oxygen Species (ROS) Generation. *J. Phys. Chem. C* **2025**, *129*, 20949–20959. [\[CrossRef\]](#)
155. Liu, J.; Ruan, H.; Duan, P.; Shao, P.; Zhou, Y.; Wang, Y.; Chen, Y.; Yan, Z.; Liu, Y. Photocatalytic Degradation of Antibiotics Using Nanomaterials: Mechanisms, Applications, and Future Perspectives. *Nanomaterials* **2025**, *16*, 49. [\[CrossRef\]](#) [\[PubMed\]](#)
156. Bhattacharjee, J.; Roy, S.; Shaikh, A.A. Artificial Intelligence and Machine Learning for the Optimization of Photocatalytic Performance. *Energy* **2025**, *360*, 100027. [\[CrossRef\]](#)
157. Liu, W.; Wang, B.; Yangjin, D.; Zhan, S. Machine Learning Assists in the Design of Photocatalysts for Environmental Remediation: A Comprehensive Review. *Environ. Microb. Technol.* **2025**, *1*, 2. [\[CrossRef\]](#)
158. Zhang, X.; Liu, Z.; Shao, B.; Liang, Q.; Wu, T.; Pan, Y.; He, Q.; He, M.; Ge, L.; Huang, J. Porphyrin-Based Metal–Organic Framework Photocatalysts: Structure, Mechanism and Applications. *Small Methods* **2025**, *9*, 2402096. [\[CrossRef\]](#) [\[PubMed\]](#)
159. Dang, Z.; Wei, L.; Ou, J.; Han, L.; Liu, C.; Zhu, L. Fundamentals, Emerging Regulation Strategies of Porphyrin-Structured Materials for Enhanced Photocatalysis. *Adv. Synth. Catal.* **2026**, *368*, e70511. [\[CrossRef\]](#)
160. Garg, R.; Sabouni, R.; Alaamer, A.; Alali, A.; Al-Muqbel, D.; Alqassem, H.; Almazrooei, K. Recent Development in Metal–Organic Framework-Based Hybrid Nanocomposites for Pollutants Remediation from Wastewater: Challenges and Opportunities. *Environ. Technol. Innov.* **2023**, *32*, 103446. [\[CrossRef\]](#)

161. Pieczyńska, A.; Baluk, M.A.; Mazierski, P.; Miodyńska-Melzer, M.; Cavdar, O.; Klimczuk, T.; Nikiforow, K.; Matus, K.; Zaleska-Medynska, A. PCN-222 Thin Film on Ceramic Foam for Removal of Disinfection by-Products by Sorption and Photocatalysis under Visible Light. *Chem. Eng. J.* **2026**, *527*, 171544. [[CrossRef](#)]
162. Abbas, M.; Liang, Z.; Chen, M.; Qu, W.; Khan, S.; Ashaq, M.S.; Chen, D.; Xie, S. Toxicity Challenges and Current Advancement in Metal–Organic Frameworks (MOFs) for Biomedical Applications. *Biol. Trace Elem. Res.* **2025**, *204*, 836–852. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.