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**Review Article**

# Metal–Organic Frameworks in Photocatalytic Water Purification: Antibiotic Elimination, Metal Leaching Risks, and Environmental Safety

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## Abstract

Antibiotic residues in wastewater and receiving waters are an environmental concern because their persistence can contribute to ecological exposure and the selection and dissemination of antimicrobial resistance. Conventional wastewater treatment processes do not consistently eliminate all antibiotic compounds, and treatment performance varies with antibiotic class, wastewater composition, and plant configuration. Metal–organic frameworks (MOFs), crystalline porous materials assembled from metal-containing nodes and organic linkers, have attracted interest as adsorbents and photocatalyst components because their pore structures, surface chemistry, and optical properties can be tailored. Under suitable illumination, photoactive MOFs and MOF-based composites can generate electron–hole pairs and reactive oxygen species (ROS), which may transform antibiotics such as tetracyclines, fluoroquinolones, and sulfonamides. However, antibiotic removal is not synonymous with complete mineralisation or detoxification. Framework hydrolysis, linker degradation, nanoparticle release, and metal leaching may introduce secondary environmental risks. This review discusses the structural and photophysical features that govern MOF photocatalysis, the proposed mechanisms of antibiotic transformation, and the use of heterojunctions to improve charge separation. It also examines aqueous stability, metal and linker release, transformation-product toxicity, and the limitations of laboratory performance measurements. Finally, it considers material-design and process-engineering approaches including more stable metal nodes, safer linkers, protective composites, catalyst immobilisation, and systematic post-treatment assessment that may help move MOF-based photocatalysis towards environmentally responsible water treatment.

**Keywords:** Metal–Organic Frameworks, Photocatalysis, Antibiotics, Wastewater Treatment, Reactive Oxygen Species, Heterojunctions, Hydrolytic Stability, Metal Leaching, Transformation Products, Environmental Safety.

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## 1. INTRODUCTION AND BACKGROUND

Antibiotics enter aquatic environments through several pathways, including municipal wastewater, hospital discharges, pharmaceutical manufacturing, livestock production, and agricultural runoff. Frequently investigated groups include tetracyclines, fluoroquinolones, sulfonamides, macrolides, and β-lactam antibiotics. Their environmental occurrence is variable: concentrations depend on antibiotic consumption, local wastewater infrastructure, industrial activity, hydrology, and the performance of treatment processes [1, 2]. Wastewater treatment plants are important barriers to contaminant release, but conventional biological treatment does not remove all antibiotics consistently. Some compounds or their transformation products may remain in treated effluent or be transferred to sewage sludge [1–3].

Antibiotic residues are relevant to environmental and public health because exposure of microbial communities to antimicrobial compounds can contribute to selection pressure for antimicrobial resistance. Wastewater treatment systems may also contain antibiotic-resistant bacteria and resistance genes, making the management of antibiotic-contaminated wastewater part of a broader One Health challenge [3]. Nevertheless, the presence of an antibiotic in water does not, by itself, establish that resistance will develop; risk depends on exposure concentration, duration,

bioavailability, microbial ecology, and other environmental factors.

Conventional treatment processes including biological activated sludge, sedimentation, and filtration are designed primarily to reduce organic load, suspended solids, and microbial contamination. Their effectiveness for individual pharmaceutical micropollutants varies. This has stimulated interest in advanced treatment approaches such as adsorption, membrane separation, ozonation, electrochemical oxidation, and photocatalytic advanced oxidation processes (AOPs) [2-6].

Photocatalysis uses light-activated materials to promote oxidation and reduction reactions at or near a catalyst surface. Semiconductor photocatalysts such as titanium dioxide ($TiO_2$), zinc oxide (ZnO), and graphitic carbon nitride (g-$C_3N_4$) have been widely investigated. Their performance can be constrained by limited absorption of visible light, rapid recombination of photogenerated charge carriers, and insufficient interaction between pollutants and active surface sites [11, 12]. These limitations are not identical for every catalyst, and modified or composite semiconductors can address some of them.

Metal–organic frameworks (MOFs) offer an alternative materials platform. They consist of metal ions or metal-containing clusters coordinated to organic linkers, producing crystalline networks with tunable pore structures and chemical functionality [4]. Some MOFs can adsorb pollutants, absorb light, or act as supports for other photoactive materials. Their properties can be modified through linker functionalization, metal-node selection, defect engineering, and composite formation [5–10].

The promise of MOFs must, however, be considered alongside their behavior in water. A framework that performs well in a short laboratory experiment may undergo structural changes during prolonged exposure to water, dissolved salts, natural organic matter, variable pH, or repeated photocatalytic cycling. Such changes may release metal ions, organic linkers, or fine particles. Therefore, the assessment of MOF photocatalysts should include not only antibiotic removal but also catalyst stability, transformation-product identification, leaching, and post-treatment toxicity [19–24].

**Table 1: Potential benefits and environmental concerns associated with MOF-based photocatalytic water treatment**

| Potential benefits | Associated limitations or risks |
|---|---|
| Tunable pore size, surface chemistry, and porosity | Pore blockage by natural organic matter or co-contaminants |
| Adsorption of pollutants near catalytic sites | Adsorption may be mistaken for chemical degradation |
| Adjustable optical and electronic properties | Not all MOFs are photoactive or absorb visible light effectively |
| Possibility of forming semiconductor heterojunctions | Charge-transfer pathways depend on actual band alignment and interface quality |
| Potential for antibiotic transformation under illumination | Transformation products may remain biologically active or toxic |
| Modular selection of metal nodes and linkers | Hydrolysis, linker degradation, metal leaching, and particle release |
| Composite formation and catalyst immobilization | Additional synthesis steps, cost, and possible mass-transfer limitations |

## 2. Structural Principles and Bandgap Tuning of MOFs

### 2.1. Fundamental Structure

MOFs are constructed from inorganic secondary building units (SBUs), such as metal ions or metal–oxo clusters, connected by organic linkers. Common linker families include carboxylates, azolates, and phosphonates. The selection of metal node, linker geometry, coordination environment, and synthesis conditions determines the resulting framework topology and properties [4-8].

Representative frameworks include UiO-type materials, MIL-type materials, and zeolitic imidazolate frameworks (ZIFs). These materials should not be treated as interchangeable: their metal–linker bonds, pore structures, optical properties, and resistance to water differ substantially.

**Metal Nodes + Organic Linkers → Ordered Porous Coordination Framework**

Examples of components include Zr-, Fe-, Ti-, Cu-, and Zn-containing nodes and linkers such as terephthalate, aminoterephthalate, and porphyrin-based ligands. The suitability of any particular framework for photocatalytic water treatment depends on its stability, light absorption, redox properties, pollutant affinity, and possible release of its constituent elements.

### 2.2. Structural and Photophysical Features Relevant to Photocatalysis

The high internal surface area of some MOFs can support adsorption and provide access to catalytic sites. However, surface area alone is not a reliable predictor of photocatalytic performance. Pore accessibility, adsorption strength, charge-carrier lifetime, optical absorption, and the energetics of surface reactions must also be considered [5-13].

**Table 2: Structural features of MOFs and their possible roles in photocatalysis**

| Structural or electronic feature | Characteristic | Potential relevance to photocatalysis |
|---|---|---|
| Porosity and surface area | Framework-dependent pore volume, pore dimensions, and accessible surface | May increase pollutant adsorption and contact with active sites |
| Linker functionalisation | Introduction of groups such as $–NH_2$ or other electron-donating or electron-withdrawing substituents | Can modify light absorption and electronic structure |
| Metal-node composition | Selection of metal ions or clusters | Influences coordination strength, redox chemistry, and stability |
| Charge-transfer behavior | Ligand-to-metal or metal-to-ligand electronic transitions in suitable systems | Can support photoexcitation and charge separation |
| Defects and coordinatively unsaturated sites | Missing linkers, missing clusters, or accessible metal centres | May alter adsorption and catalytic activity, but can also reduce stability |
| Composite interfaces | Contact between MOFs and semiconductors, carbon materials, or other functional phases | May improve light harvesting and charge-carrier separation |

### 2.3. Charge-Transfer Pathways

The electronic behaviour of a MOF depends on the metal node, organic linker, coordination environment, and electronic coupling between framework components. Several charge-transfer processes may contribute to photoactivity.

**Ligand-to-Metal Charge Transfer (LMCT):**

Following light absorption, an electron associated with an excited organic linker may transfer to an available metal-centred acceptor state. This process can facilitate charge separation in appropriately designed MOFs. The efficiency of LMCT depends on the relative energies of the linker and metal-centred orbitals and on the structure of the framework [18].

**Metal-to-Ligand Charge Transfer (MLCT):**

In suitable systems, photoexcitation can transfer electron density from metal-centred orbitals to ligand-centred orbitals. Whether this process is important depends on the electronic structure of the specific metal–linker combination.

**Semiconductor-Like Band Transitions:**

Certain conductive or electronically coupled MOFs exhibit band structures in which the valence- and conduction-band states have contributions from both metal and linker orbitals. This description should not be generalised to every MOF, because many frameworks behave as molecular or insulating solids rather than conventional semiconductors [13-18].

### 2.4. Bandgap Engineering

The optical response of a MOF can be adjusted through linker functionalisation, metal substitution, defect formation, photosensitisation, or formation of a composite with another semiconductor. For example, amino-functionalised linkers can change the absorption profile of selected frameworks. Such modification does not automatically guarantee efficient visible-light photocatalysis: the resulting band-edge positions must still support the desired redox reactions, and the excited charges must survive long enough to reach reactive sites [13-18].

A useful evaluation therefore combines optical absorption measurements with band-edge estimation, photoluminescence, transient photocurrent, electrochemical impedance spectroscopy, and appropriate radical-scavenging or electron-paramagnetic-resonance measurements.

## 3. Mechanisms of Photocatalytic Antibiotic Elimination

### 3.1. Generation of Photogenerated Charge Carriers

When a photoactive MOF or MOF-based semiconductor absorbs a photon with sufficient energy, an electron may be promoted from an occupied state to a higher-energy state, leaving behind a hole:

$$\textbf{Photocatalyst} + h\nu \rightarrow e^- + h^+$$

The excited electrons and holes can participate in reduction and oxidation reactions, respectively. They may also recombine, dissipating the absorbed energy without contributing to pollutant transformation. The competition between charge generation, recombination, transport, and surface reaction is a central determinant of photocatalytic efficiency [11–13].

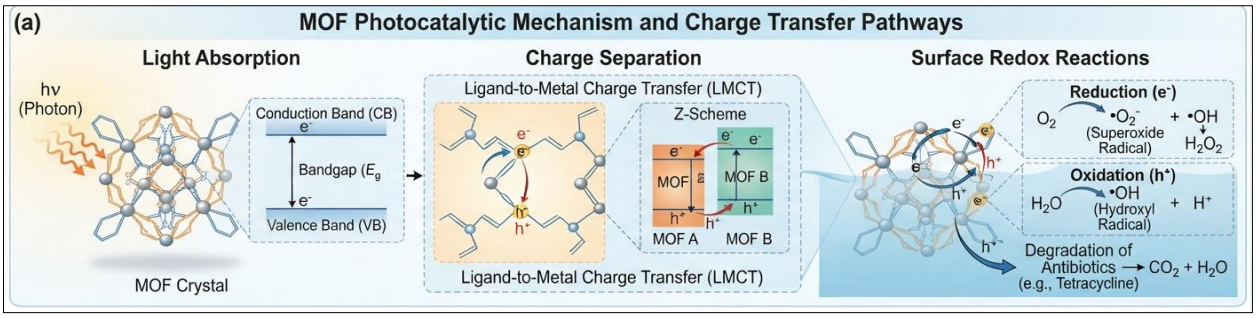


**Figure 1: Photocatalytic Mechanisms in MOFs. (a) Schematic illustration of light absorption, charge separation (LMCT and Z-scheme), and the subsequent surface redox reactions generating ROS to mineralise antibiotic pollutants**

### 3.2. Reactive Oxygen Species Generation

Depending on the photocatalyst's band-edge positions, solution chemistry, and available electron donors or acceptors, photogenerated charge carriers may participate in the formation of reactive oxygen species (ROS). Important species include superoxide radicals ($•O_2^-$), hydroxyl radicals (•OH), and singlet oxygen ($^1O_2$). Direct oxidation by photogenerated holes ($h^+$) may also contribute.

Representative reactions include:

**1. Superoxide radical formation**

$$\mathbf{O_2 + e^- \rightarrow •O_2^-}$$

A photogenerated electron reduces dissolved molecular oxygen ($O_2$), producing the superoxide radical anion ($•O_2^-$).

**2. Hydroxyl radical formation**

**Pathway A: Oxidation of water**

$$\mathbf{H_2O + h^+ \rightarrow •OH + H^+}$$

A photogenerated hole ($h^+$) oxidises water, generating a hydroxyl radical (•OH) and a proton ($H^+$).

**Pathway B: Oxidation of hydroxide ions**

$$\mathbf{OH^- + h^+ \rightarrow •OH}$$

A photogenerated hole oxidises a hydroxide ion ($OH^-$), producing a hydroxyl radical.

These reactions are feasible only when the relevant charge-carrier potentials and solution conditions permit them. In particular, hydroxyl-radical production requires sufficiently oxidising holes. Singlet oxygen can arise through energy-transfer or oxygen-centred reaction pathways, but its formation should be demonstrated for the specific photocatalytic system rather than assumed from the presence of superoxide alone [11-13].

ROS can attack antibiotic molecules through hydroxylation, dealkylation, oxidation, bond cleavage, and ring-opening reactions. The relative importance of individual species is catalyst- and pollutant-dependent and is commonly investigated using scavenger experiments, electron-paramagnetic-resonance spectroscopy, and product analysis [6-16].

### 3.3. Transformation of Major Antibiotic Classes

Antibiotics have different functional groups and molecular structures; therefore, their photocatalytic transformation pathways are not identical. The following pathways describe commonly investigated types of reactions rather than universal mechanisms.

**Table 3: Representative antibiotic classes and possible photocatalytic transformation reactions**

| Antibiotic class | Representative compounds | Structural features relevant to transformation | Possible photocatalytic reactions |
|---|---|---|---|
| Tetracyclines | Tetracycline (TC), oxytetracycline (OTC) | Conjugated ring system, hydroxyl groups, and dimethylamino substituent | Hydroxylation, oxidation of amino substituents, dealkylation, ring modification, and eventual ring opening |
| Fluoroquinolones | Ciprofloxacin (CIP), norfloxacin (NOR) | Quinolone core, carboxyl group, fluorine substituent, and piperazinyl group | Oxidation or cleavage of the piperazinyl group, hydroxylation, decarboxylation, and modification of the quinolone structure |
| Sulfonamides | Sulfamethoxazole (SMX), sulfadiazine (SDZ) | Sulfonamide linkage and aromatic or heteroaromatic groups | Hydroxylation, oxidation, cleavage or transformation of the sulfonamide linkage, and subsequent aromatic-ring modification |

These pathways are supported by studies of antibiotic photodegradation, but the exact products and reaction sequence depend on the catalyst, light source, pH, dissolved oxygen, and water matrix [6–16]. Liquid chromatography–mass spectrometry (LC–MS) or high-resolution LC–MS is therefore important for identifying transformation products rather than inferring degradation solely from the disappearance of the parent compound.

### 3.4. Antibiotic Removal is Not Equivalent to Mineralisation

A decrease in the measured concentration of an antibiotic may reflect adsorption, direct photolysis, photocatalytic transformation, or a combination of these processes. It does not necessarily demonstrate complete mineralisation. Mineralisation refers to the conversion of organic carbon into inorganic end products, such as carbon dioxide and water, together with inorganic ions derived from heteroatoms.

For this reason, photocatalytic studies should distinguish among:

1. **Adsorption:** transfer of the antibiotic from the aqueous phase to the catalyst surface.
2. **Parent-compound degradation:** chemical transformation of the original antibiotic.
3. **Transformation-product formation:** production of intermediate compounds during degradation.
4. **Mineralisation:** conversion of organic matter towards inorganic end products.
5. **Detoxification:** reduction in the biological or ecological toxicity of the treated water.

A convincing assessment should combine parent-compound analysis with total organic carbon (TOC) or dissolved organic carbon measurements, transformation-product analysis, and suitable toxicity tests [6–16].

## 4. Advanced Heterojunction and Structural Strategies

Pristine MOFs may show limited visible-light absorption or rapid charge-carrier recombination. One approach to improving photocatalytic performance is to construct a heterojunction between a MOF and another semiconductor or functional material. The interface can influence charge transfer, light absorption, adsorption, and the availability of reactive sites [9-17].

### 4.1. Type-II Heterojunctions

A Type-II heterojunction involves two materials with staggered band-edge positions. Following excitation, electrons may transfer towards the material with the lower-energy conduction-band edge, while holes migrate towards the material with the higher-energy valence-band edge. This spatial separation can reduce electron–hole recombination.

A potential limitation is that the remaining electrons and holes may have weaker reduction and oxidation potentials than those retained in a Z-scheme or S-scheme arrangement. Consequently, improved charge separation does not necessarily mean stronger redox chemistry [17].

### 4.2. Direct Z-Scheme Heterojunctions

In a direct Z-scheme system, selected lower-energy electrons and holes recombine across the interface, leaving more strongly reducing electrons and more strongly oxidising holes available for surface reactions. This arrangement may preserve redox capacity while improving charge separation. The proposed mechanism should be supported by band-edge analysis and experimental evidence rather than inferred from photocatalytic performance alone [17-25].

### 4.3. S-Scheme Heterojunctions

S-scheme heterojunctions are commonly described in terms of Fermi-level equilibration, interfacial charge redistribution, band bending, and an internal electric field. These features can favour the selective recombination of less energetic charge carriers while retaining carriers with stronger redox ability. MOF-based S-scheme systems are an active area of photocatalysis research [17, 18].

**Table 4: Comparison of heterojunction strategies for MOF-based photocatalysis**

| Heterojunction type | General charge-transfer concept | Potential advantage | Main consideration |
|---|---|---|---|
| Type-II | Electrons and holes migrate to different components according to staggered band alignment | Spatial charge separation | May reduce the redox strength of retained carriers |
| Direct Z-scheme | Less energetic electrons and holes recombine across the interface | Can retain strongly reducing and oxidising carriers | Requires suitable interfacial contact and evidence for the proposed pathway |
| S-scheme | Interfacial electric field and band bending promote selective charge-carrier recombination | May combine charge separation with strong redox capacity | Mechanistic assignment requires evidence for band bending and interfacial charge redistribution |

### 4.4. Examples of MOF-Based Antibiotic Photocatalysts

Research has demonstrated that MOF-containing composites can transform antibiotics under laboratory irradiation conditions. For example, Chen and colleagues investigated $MoS_2$/ZIF-8 hybrid materials for the photocatalytic degradation of ciprofloxacin and tetracycline hydrochloride. Their study reported improved degradation relative to the comparison materials and examined transformation products [14]. A separate study constructed a MOF-on-MOF-based double Z-scheme system for visible-light-driven ofloxacin degradation [25]. More recently, an $NH_2$-MIL-101(Fe)/nitrogen-doped carbon nanodot composite was

investigated for fluoroquinolone removal and reported 97.9% ciprofloxacin degradation within 180 minutes under the study's visible-light conditions [26].

These results demonstrate the potential of MOF-based photocatalysts, but reported percentages should not be compared directly without considering the initial antibiotic concentration, catalyst dose, irradiation spectrum and intensity, reaction time, pH, water composition, and analytical method.

**Table 5: Selected examples of MOF-based photocatalytic antibiotic studies**

| Photocatalyst or material system | Target antibiotic(s) | Reported finding | Interpretation and limitation |
|---|---|---|---|
| $MoS_2$/ZIF-8 hybrid | Ciprofloxacin and tetracycline hydrochloride | Improved photocatalytic degradation compared with the relevant comparison materials; transformation products were investigated | Demonstrates the potential of a MOF–semiconductor hybrid; results are specific to the reported experimental conditions [14] |
| UiO-66-on-MIL-125/g-$C_3N_4$ double Z-scheme system | Ofloxacin | Visible-light-driven ofloxacin degradation was reported | Illustrates a multi-component charge-transfer design; performance depends on the prepared interface and reaction conditions [25] |
| $NH_2$-MIL-101(Fe)/N-doped carbon nanodots | Ciprofloxacin | 97.9% degradation in 180 minutes under visible light | A promising laboratory result; percentage removal alone does not establish complete mineralisation or detoxification [26] |

## 5. Metal Leaching Risks, Hydrolytic Instability, and Environmental Safety

### 5.1. Aqueous Stability of MOFs

The environmental suitability of a MOF photocatalyst depends partly on its ability to retain structural integrity during contact with water. Water stability varies with metal–linker bond strength, framework connectivity, pore structure, defects, pH, temperature, ionic composition, and the presence of competing ligands [19–23].

Some frameworks, including selected Zr-based materials, are often investigated for their comparatively strong metal–oxygen coordination. Other frameworks may be more susceptible to hydrolysis. However, a framework's reputation for water stability should not replace direct testing under the intended treatment conditions. Stability in pure water does not necessarily predict behaviour in wastewater containing salts, natural organic matter, phosphate, carbonate, or other competing species [20–23].

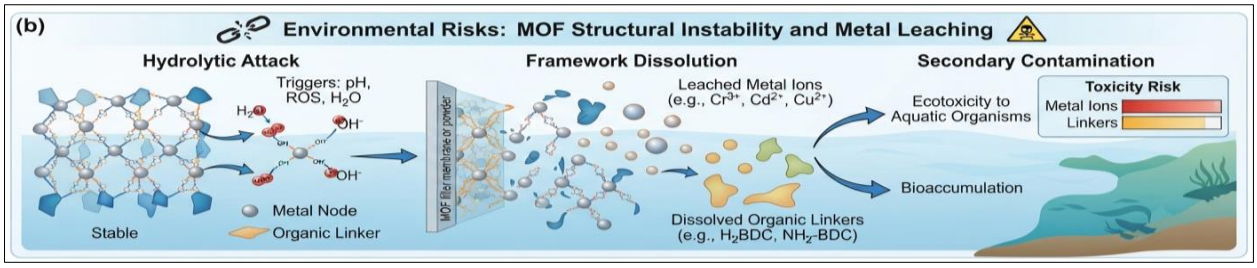


**Figure 2: Environmental and Safety Risks of MOF Instability. (a) Breakdown of the MOF framework via hydrolytic attack, leading to the leaching of toxic metal ions and organic linkers, resulting in secondary aquatic contamination and ecotoxicity**

### 5.2. Mechanisms of Framework Degradation

Several processes may contribute to framework deterioration:

**Hydrolytic Attack:** Water molecules may interact with metal–linker coordination bonds, promoting ligand displacement or bond cleavage.

**pH-Dependent Destabilisation:** Acidic conditions can protonate coordinating groups such as carboxylates or azolates, weakening metal–linker interactions. Alkaline conditions can also destabilise some frameworks through changes in metal coordination, linker chemistry, or precipitation reactions. The pH threshold is material-specific and should not be generalised across all MOFs [19–23].

**Competitive Ligand Exchange:** Phosphate, carbonate, natural organic matter, and other dissolved ligands may interact with metal centres or compete with framework linkers.

**Photocatalytic Self-Degradation:** Reactive species generated during photocatalysis may also attack susceptible organic linkers or surface coatings. This

possibility requires direct evidence for the material under investigation.

**Physical Loss of Particles:** Poorly immobilised or recovered MOF particles may escape with treated water, even when the framework remains chemically intact.

**Table 6: Potential causes and consequences of MOF degradation in aqueous treatment systems**

| Stressor | Possible structural or chemical effect | Potential environmental consequence |
|---|---|---|
| Water exposure | Hydrolysis or weakening of metal–linker coordination | Loss of crystallinity, porosity, or catalytic performance |
| Acidic pH | Protonation of coordinating linker groups | Linker displacement and framework destabilisation |
| Alkaline pH | Changes in metal coordination or formation of metal hydroxide phases | Structural alteration and possible loss of active sites |
| Dissolved salts and competing ligands | Ion exchange or competitive coordination | Changes in adsorption, stability, and metal release |
| Reactive oxygen species | Oxidation of susceptible organic components | Linker or coating degradation |
| Repeated irradiation and reuse | Accumulated chemical and physical stress | Declining activity and increased release risk |
| Inadequate particle recovery | Escape of catalyst particles from the treatment unit | Secondary particulate contamination |

### 5.3. Metal Leaching and Potential Toxicity

The release of metal species is a key consideration when MOFs are used in water treatment. Depending on the framework composition and degradation conditions, released species may include zinc, copper, cobalt, nickel, chromium, iron, or other constituent metals. The toxicity of a released metal depends on its concentration, oxidation state, chemical speciation, complexation, bioavailability, and exposure duration.

It is therefore important not to assume that every chromium-containing MOF releases hexavalent chromium, or that every metal ion released from a framework presents the same level of risk. Metal speciation and dissolved concentration should be measured directly. Where relevant, total metal concentrations and oxidation-state-specific measurements should be distinguished.

Potential environmental effects of metal release include toxicity to aquatic microorganisms, algae, invertebrates, and fish. The actual risk should be assessed using measured leaching data and relevant ecotoxicological endpoints rather than inferred from the metal's presence in the original framework [19–24].

### 5.4. Organic Linker Release and Secondary Products

Framework deterioration may also release organic linkers or linker-derived compounds. Their environmental effects depend on chemical identity, concentration, persistence, and biodegradability. It is not scientifically justified to classify all imidazole-, pyridine-, or terephthalate-based linkers as endocrine disruptors or as uniformly toxic. Each released compound requires an appropriate hazard assessment.

In addition, photocatalytic treatment can generate transformation products from the target antibiotic. These products may be less toxic, similarly toxic, or more toxic than the parent compound. The direction of toxicity change cannot be predicted reliably from parent-compound disappearance alone [14–16].

### 5.5. Environmental Safety Assessment

A complete environmental assessment should evaluate both the treated water and the catalyst after use. At minimum, a study should report:

- Dissolved metal concentrations before and after photocatalytic treatment.
- Changes in framework crystallinity and morphology after reuse.
- Evidence of linker release or degradation where relevant.
- Catalyst particle recovery and potential particle escape.
- Parent-antibiotic concentration and transformation-product profiles.
- TOC or dissolved organic carbon removal.
- Toxicity of treated water using suitable biological test organisms.
- Changes in photocatalytic performance across repeated cycles.

The stability of MOFs is affected by water-matrix composition, and the selected stability test can influence the conclusion. A single X-ray diffraction measurement or a short-term reuse experiment is therefore insufficient to establish long-term environmental safety [20–23].

## 6. Green Chemistry Solutions and Future Outlook

The development of environmentally responsible MOF photocatalysts requires a balance between catalytic performance, chemical stability,

recoverability, and low toxicity. Improving antibiotic degradation while ignoring catalyst-derived contamination would simply exchange one water-quality problem for another.

### 6.1. Selection of Metal Nodes

Material design can prioritise metal nodes with comparatively favourable toxicity profiles and strong coordination chemistry. Zr(IV) and Ti(IV)-based frameworks are frequently investigated because of their strong metal–oxygen interactions, while selected Fe-based materials are attractive because iron is widely available and can participate in redox chemistry [19–23]. Nevertheless, no metal should be described as inherently harmless under all conditions. Its released concentration, speciation, and exposure context remain important.

### 6.2. Bio-Based and Safer Organic Linkers

Renewable or bio-derived precursors may offer opportunities to reduce the environmental footprint of MOF synthesis. Candidate sources include selected amino-acid-derived compounds, naturally occurring polyphenols, and other renewable organic building blocks. The use of a bio-derived precursor does not automatically make the resulting framework non-toxic or biodegradable. The final material, its degradation products, and its synthesis route all require assessment [10-27].

### 6.3. Protective Coatings and Composite Formation

Protective coatings or composite structures may reduce direct exposure of vulnerable coordination bonds to water and improve particle handling. Possible approaches include polymer coatings, silica-based shells, and integration with other stable support materials. Coating design must preserve access of light, oxygen, and pollutants to the catalytic sites; an overly dense coating may improve stability while reducing photocatalytic activity.

### 6.4. Immobilisation and Recovery Systems

Immobilising MOF particles on suitable supports can reduce catalyst loss and simplify separation after treatment. Potential supports include polymer membranes, electrospun nanofibres, hydrogels, ceramic substrates, and magnetic components. Magnetic recovery may be useful where magnetic phases can be incorporated without compromising photocatalytic activity or introducing additional leaching concerns [5-10].

### 6.5. Real Wastewater and Continuous-Flow Testing

Most laboratory studies use simplified aqueous solutions containing a single antibiotic. Real wastewater contains multiple contaminants, dissolved salts, suspended solids, natural organic matter, and microorganisms. These components can compete for adsorption sites, absorb or scatter light, quench ROS, and alter catalyst stability. Therefore, performance in synthetic water should be treated as an initial proof of concept rather than evidence of full-scale readiness [2-10].

Future studies should progress from single-solute batch experiments to mixed-contaminant systems, real wastewater, longer-term reuse tests, and continuous-flow reactors. Process evaluation should include energy demand, catalyst recovery, metal and linker release, treatment by-products, and cost.

**Table 7: Green engineering strategies and the evidence needed to evaluate them**

| Strategy | Intended benefit | Important validation requirements |
|---|---|---|
| More hydrolytically stable metal nodes and frameworks | Reduce structural breakdown and metal release | Long-term water stability, metal leaching, and post-use structural analysis |
| Safer or renewable linker precursors | Reduce the environmental footprint of material synthesis | Linker toxicity, degradation products, synthesis solvents, and life-cycle considerations |
| Protective coatings and core–shell structures | Limit water attack and improve particle integrity | Coating stability, light penetration, pollutant access, and coating-derived leaching |
| Magnetic or substrate-assisted recovery | Reduce catalyst escape and simplify separation | Particle recovery efficiency, magnetic-phase stability, and repeated-cycle performance |
| Membrane or fibre immobilisation | Enable easier handling and potential continuous operation | Pressure drop, fouling, mass transfer, catalyst retention, and long-term stability |
| Real wastewater testing | Establish performance under realistic conditions | Matrix effects, mixed pollutants, toxicity, energy demand, and operational cost |

### 6.6. Recommended Minimum Reporting Framework

For meaningful comparison between studies, future research should report a consistent set of experimental and environmental indicators.

**Table 8: Recommended parameters for evaluating MOF-based photocatalytic antibiotic treatment**

| Evaluation category | Recommended measurements |
|---|---|
| Catalyst characterisation | X-ray diffraction, microscopy, surface area and porosity, elemental composition, and optical absorption |
| Photocatalytic conditions | Light source and spectrum, light intensity, pH, temperature, dissolved oxygen, catalyst dose, and initial antibiotic concentration |
| Adsorption controls | Dark adsorption equilibrium and photolysis control without catalyst |
| Photocatalytic performance | Parent-compound removal, reaction kinetics, and performance under comparable conditions |
| Mechanistic evidence | Radical-scavenging tests, electron-paramagnetic-resonance measurements where available, and charge-carrier characterisation |
| Mineralisation | TOC or dissolved organic carbon measurements |
| Transformation products | LC–MS or high-resolution LC–MS identification and proposed transformation pathways |
| Material stability | Post-reaction crystallinity, morphology, surface chemistry, and activity over repeated cycles |
| Leaching and particle release | Dissolved metal analysis, linker release where relevant, and particle-retention measurements |
| Environmental safety | Ecotoxicity testing of treated water and assessment of catalyst-derived contaminants |
| Scale-up potential | Real wastewater tests, continuous-flow operation, energy consumption, recovery efficiency, and cost analysis |

## 7. CONCLUSION

Metal–organic frameworks offer a versatile platform for the development of photocatalytic materials for antibiotic-contaminated water. Their tunable metal nodes, organic linkers, pore structures, and potential for composite formation provide opportunities to improve pollutant adsorption, light utilisation, and charge-carrier separation. Research on MOF-based heterojunctions has demonstrated the potential to transform antibiotics including tetracyclines, fluoroquinolones, and sulfonamides under laboratory conditions.

However, high antibiotic removal percentages should not be interpreted as proof of complete mineralisation or environmental detoxification. The transformation products of antibiotics may retain biological activity, while degradation of the MOF itself may release metal species, organic linkers, or particles into treated water. These risks are framework-specific and depend on water chemistry, irradiation conditions, and operating time.

Future development should therefore prioritise stable and appropriately selected metal nodes, safer linker chemistry, protective composite design, efficient catalyst immobilisation, and rigorous recovery systems. Equally important are systematic measurements of metal leaching, transformation products, mineralisation, and post-treatment toxicity. Testing in real wastewater and continuous-flow systems will be essential to determine whether MOF-based photocatalysis can provide an effective, safe, and sustainable contribution to advanced water treatment.

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