Transactions on Environment, Energy and Earth Sciences
ISSN: 2960-1924, eISSN: 2960-2300 | Volume 5
EMCEME 2025

Research Status and Prospect of Fluorescence Detection of Antibiotics Based on Metal-Organic Frameworks (MOFs)

Deji Yan *

School of Materials Science and Engineering, Hefei University of Technology, Hefei, China, 230009

* Corresponding Author Email: ycdjhfut@163.com

Abstract. Antibiotic residues pose a serious threat to the ecological environment and human health. The development of rapid and sensitive detection methods is of great significance. This paper systematically reviews the research progress of fluorescence sensing platforms based on Metal-Organic Frameworks (MOFs) in antibiotic detection in recent years, with emphasis on their luminescence mechanisms and sensing principles, and analyzes the regulatory effects of ligand design, metal center selection and pore engineering on detection performance, and then proposes structure-performance optimization strategies to provide new ideas for the rational design of highly selective MOFs sensors. The typical applications of this type of material in the detection of tetracyclines, quinolones, sulfonamides, nitroimidazoles and nitrofurans are summarized, demonstrating its high sensitivity, excellent selectivity and fast response characteristics. And through efficient identification verification of trace antibiotics in complex matrices such as water and food, it provides a technical path for the MOFs sensing platform to transform from laboratory research to actual detection. This review particularly highlights the significant breakthroughs of MOFs in multimodal analysis, visualization and field detection, and looks forward to the current challenges and future development directions, providing a reference for the continuous innovation in this field.

Keywords: Metal-Organic Frameworks, Fluorescence Detection, Antibiotics, Sensing Mechanism, Field Detection.

1. Introduction

Antibiotics are the cornerstone of modern medicine and animal husbandry and are crucial for the prevention and treatment of infectious diseases. But the global abuse problem has led to residual antibiotics entering ecosystems through food chains like animal-derived foods and environmental emissions including medical wastewater, aquaculture excrement [1]. These residual antibiotics are difficult to degrade in the environment and enter the human body through bioaccumulation, which can cause allergic reactions, compromised immune systems, genetic problems and the crisis of drug resistance [2]. Tetracycline antibiotics, for example, have been overused in the livestock industry and are widely present in water, soil and animal products, directly threatening human health [3]. As a result, antibiotic contamination has become a major challenge to global public health and ecological security. Given the hidden and cumulative hazards of antibiotic residues, the development of efficient and precise detection technologies is an urgent need to ensure food safety, environmental quality and human health [4]. In particular, real-time monitoring of trace antibiotics in food, drinking water and medical wastewater can effectively break the chain of contamination transmission and provide data support for the prevention and control of drug resistance [5]. At present, regulatory authorities in various countries continue to tighten antibiotic residue limits, further highlighting the necessity of highly sensitive detection technologies. The current mainstream antibiotic detection methods include high performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), and electrochemical immunoassay. Although these methods perform well in terms of accuracy, they are difficult to widely adopted due to their complex operation process, high cost, and high reliance on the support of large instruments and professional operators [6,7]. In addition, these techniques involve complex sample pretreatment processes, strict requirements for sample standards, and poor field adaptability, making it difficult to effectively meet the demand for rapid testing in field locations

such as farms and water sources. Therefore, it is imperative to develop new types of rapid, low-cost, portable testing technologies.

Metal-Organic Frameworks (MOFs) are crystalline porous materials with periodic network structures formed by the self-assembly of inorganic metal centers (metal ions or clusters) with organic ligands through coordination bonds. MOFs have high porosity, large specific surface area, good biocompatibility and chemical stability. By selecting different metal centers and organic ligands, the pore size, surface functional groups and luminescence properties of MOFs can be precisely regulated. As a fluorescence sensing platform, MOFs have significant advantages such as tunable fluorescence, high sensitivity, good selectivity and multi-functional integration. Therefore, MOFs fluorescence sensing technology offers an innovative solution for antibiotic detection. MOFs sensors enable rapid on-site detection, can be made into test strips for visual screening, and can simultaneously identify multiple targets. The sensor has been successfully applied to the detection of antibiotics in complex matrices such as milk and drug preparations, confirming its practical application value (Figure 1). This paper systematically reviews the research progress and application prospects of MOFs fluorescence sensing technology in the field of antibiotic detection. The article elaborates on the multiple luminescence mechanisms and sensing principles of MOFs fluorescence detection of antibiotics (such as Photoinduced-electron transfer PET, Förster resonance energy transfer FRET, competitive absorption CA, etc.) and delves into the influence of MOFs structural characteristics (including ligands, metal centers, pore structures) on their detection performance. At the same time, the latest applications of MOFs in the detection of tetracyclines, quinolones, sulfonamides, nitroimidazoles and other antibiotics are systematically summarized, covering high-performance sensing systems from single antibiotic identification to simultaneous detection of multiple components. The study focused particularly on MOFs sensing technologies that have the potential for rapid response, high portability and field visualization detection, such as test strips, smartphone integration platforms, ratio fluorescence and sensing arrays. The article prospectively explores the challenges and future trends in the field, including enhancing material stability, fusing multimodal sensing, and applying artificial intelligence-assisted design, and points out the technical paths and development ideas for subsequent research. This paper aims to provide theoretical basis and practical guidance for the development of efficient, sensitive and portable MOFs fluorescence sensors for real-time monitoring and intelligent management of antibiotic residues in the environment and food.

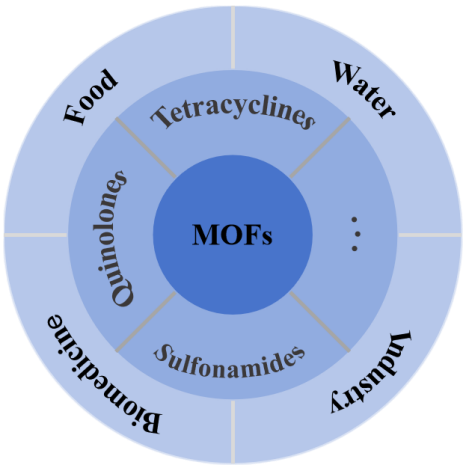


Figure 1. Application of metal-organic frameworks (MOFs) in the field of fluorescence detection of antibiotics.

2. The basic principle of MOFs fluorescence detection of antibiotics

2.1. The fluorescence generation mechanism of MOFs

Fluorescence is a phenomenon of photoluminescence (PL). Photoluminescence describes the process in which a substance can re-release a photon (or electromagnetic wave) after absorbing it. The

mechanism of molecular luminescence can be summarized as the absorption of photons and the transition of electrons from the ground state (S_0) to the excited state. As shown in Figure 2 [8], the excited states include the unstable first excited singlet (S_1) and the second excited singlet (S_2). Fluorescence is produced when electrons return from S_1 or S_2 to S_0. The fluorescence of MOFs stems from their unique organic-inorganic hybrid structure, and the luminescence mechanism can be classified into four categories.

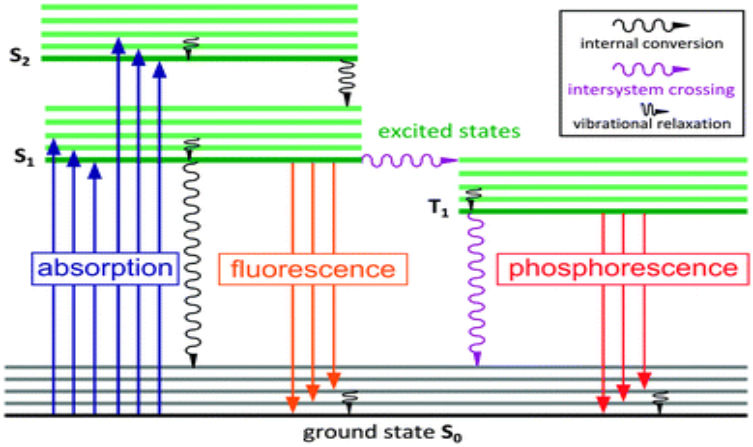


Figure 2. Jablonski diagram showing basic photophysical processes; S denotes singlet, T triplet states; internal conversion and intersystem crossing are non-radiative processes; intersystem crossings are accompanied by a forbidden change in the spin state.

2.1.1. Luminescence of organic ligands

Figure 3 shows five potential luminescence mechanisms of MOFs [9]. Organic ligands are one of the important sources of fluorescence for MOFs. When they have rigid π-π conjugated systems (e.g., aromatic or heterocyclic structures), π→π* or n→π* electron transitions occur under ultraviolet or visible light excitation, followed by the release of photons through radiative decay, resulting in fluorescence. Specifically, luminescence mainly includes the following three scenarios. The first is single ligand emission, that is, when there is no obvious charge transfer between the ligand and the metal, the emission peak of MOFs is very similar to that of the free ligand. For example, the fluorescence properties of CdMOF-1 are basically the same as those of its ligand TIAB. The second is ligand-in charge transfer, or ILCT for short, which refers to the migration of electrons between different functional groups in a single ligand system. The third is ligand-to-ligand charge transfer (LLCT), which typically occurs in mixed ligand MOFs, where an electron jumps from the π orbital of one ligand to that of another, causing a change in the emission wavelength or intensity. For example, CdMOF-2 successfully achieves this mechanism through a mixed ligand strategy [10]. It is worth emphasizing that the conjugation effect of organic ligands is particularly critical for the LLCT process, while increasing the rigidity of the ligands helps to suppress non-radiative relaxation, thereby enhancing the quantum yield of the material.

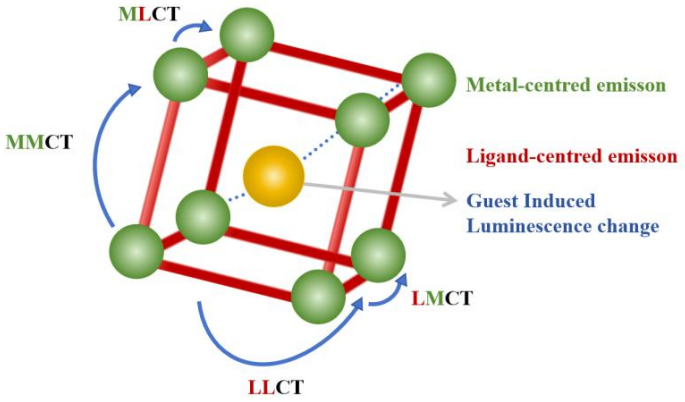


Figure 3. Five luminescence mechanisms achieved by MOFs through transitions.

2.1.2. Luminescence at the metal center

Lanthanide ions (e.g., Eu^{3+}, Tb^{3+}) are the main body of this kind of luminescence, but rely luminescence butffect" because their f-f transition is a blocking transition. Organic ligands absorb light energy and then transfer it from the singlet state (S_1) to the triplet state (T_1) through intersystem transitions (ISC) to the excited state of the lanthanide ion; lanthanide ions radiate from the excited state to the ground state and emit characteristic fluorescence, such as red light for Eu^{3+} and green light for Tb^{3+}. The triplet energy level (T_1) of the ligand must match the lowest excited state energy level of the lanthanide ion - both too small and too large energy level differences will reduce the energy transfer efficiency.

2.1.3. Charge transfer luminescence

Electrons migrating between metals and ligands can trigger luminescence, which is mainly divided into two types of mechanisms: metal-to-ligand charge transfer (MLCT) and ligand-to-metal charge transfer (LMCT). During MLCT, electrons transition from the metal's d orbital to the ligand's π^* orbital, typically resulting in a redshift in the emission spectrum, such as the transition from the Cu-3d orbital to the O-2p/N-2p orbital observed in Cu-MOFs [11]. In contrast, the transfer of electrons from the π orbitals of ligands to the d orbitals of metals in LMCT typically causes a blue shift in emission peaks, as evidenced by the luminescence of lanthanide ions sensitized by ligands in Ln-MOFs [12]. MLCT and LMCT occur in a direction that depends on the relative positions of the energy levels of the metal and the ligand: MLCT occurs when the lowest excited state energy level of the ligand is lower than that of the metal, and LMCT occurs when the energy level of the metal is lower than that of the ligand.

2.1.4. The guest molecule induces luminescence

The porous structure of MOFs can encapsulate or surface-modify luminescent guests to regulate fluorescence through host-guest interactions. Using in-situ encapsulation techniques, lanthanide ions, quantum dots, or dye molecules, such as Rh6G, Eosin Y, can be embedded into the pores of MOFs, effectively preventing their agglomeration through the spatial confinement effect [13]. Post-synthesis modification enhances luminescence stability and sensitivity by functionalizing the MOFs surface to bind fluorescent guest, such as dye-sensitized lanthanide ions [14]. The guest molecules can overcome aggregated fluorescence quenching (ACQ) and enhance fluorescence through charge transfer or RET of MOFs [9].

2.2. MOFs fluorescence detects the mechanism of antibiotics

2.2.1. Verification of skeleton stability

During the inspection process, a series of characterization methods are needed to verify the integrity of the MOFs skeleton in order to rule out non-radiative transitions that may be caused by structural collapse. Using X-ray diffraction (XRD) techniques, compare the positions of the simulated peaks of MOFs before and after detection with the actual measured peaks (ignoring the intensity factor). If the peak shapes match, it indicates that the MOFs skeleton remains intact and no collapse has occurred. For example, Wang Guojiao et al. confirmed through Powder X-ray diffraction (PXRD) that the peak position of complex 1 did not shift after identifying furantoin (NFT), proving that the fluorescence change was not caused by structural damage [5].

2.2.2. Photoinduced electron transfer (PET)

When the orbital energies of the sensor and the analyte match, the excited electrons can be transferred between the two through the PET process [15,16]. If the energy of the analyte's lowest non-occupied orbital (LUMO) is lower than that of the MOF-based sensor, the excited electrons will be transferred from the sensor to the analyte, thereby turning off the fluorescence of the sensor. Correspondingly, if the energy of the LUMO of the analyte is higher than that of the MOF-based sensor, the excited electrons will be transferred from the analyte to the sensor, thereby turning on the fluorescence of the sensor, as shown in Figure 4. For example, a zinc-based metal-organic framework (Zn-TCPE) shows

a specific response to tetracycline (TC). After the addition of TC, the fluorescence intensity of the MOF at 460 nm was significantly enhanced (about five times), and the emission peak underwent a slight blue shift. The detection limit was as low as 3.34 μM, with a linear range of 5-100 μM (R^2 > 0.99). The H4BTDI ligand-constructed Cd-MOF (Complex 1) detects nitrofurantoin (NFT) and nitrofurazolidone (NFZ). DFT calculations indicated that the LUMO level of NFT/NFZ was significantly lower than that of the H4BTDI ligand. When excited, electrons transition from HOMO to LUMO of the MOF, but the excited electrons shift from LUMO of the MOF to LUMO of the NFT/NFZ. Electrons cannot return to the ground state of the MOF, resulting in significant fluorescence quenching with a quenching constant of the order of 10^4 M^{-1}.

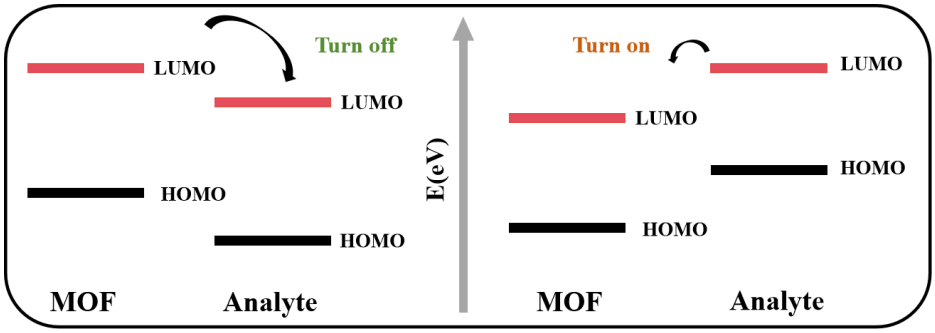


Figure 4. Pet-induced fluorescence quenching/enhancement mechanism.

2.2.3. Energy transfer

The energy transfer mechanisms mainly include Förster resonance energy transfer (FRET) and Competitive absorption (CA). In the FRET mechanism, MOFs act as donors whose emission spectra overlaps with the absorption spectra of the antibiotic (receptor) at distances of 1 to 10 nanometers. Excited-state energy is transferred to the receptor in a non-radiative manner through dipole-dipole interactions, resulting in a shortened donor fluorescence lifetime [2]. The efficiency of this energy transfer mainly depends on the degree of overlap between the emission spectrum of the MOFs and the absorption spectrum of the target analyte in the ultraviolet region. For example, Zhao found that the emission spectrum of complex 9 ($C_{128}H_{64}In_4O_{32}S_4$) overlapped with the absorption spectrum of $Cr_2O_7^{2-}$, and FRET was the main cause of its quenching [13]. The essence of CA is the competition of light energy. When the ultraviolet-visible absorption spectrum of an antibiotic molecule overlaps with the excitation spectrum of a MOFs, the two compete to absorb the energy of the same light source. At this point, the antibiotic molecule reduces the excitation energy available to the MOFs by absorbing part of the excitation light energy, resulting in a decrease in the number of excited-state electrons of the MOF, which eventually manifests as fluorescence quenching of the MOF. For example, when Zn-MOF detects metal cations (Fe^{2+} UO_2^{3+}), anions, and antibiotics, a positive correlation between spectral overlap and quenching efficiency is observed, confirming that competitive absorption is the main mechanism [17]. In flexible polycarboxylic acid ligand MOFs (e.g., complex 5), the absorption range of antibiotics including oxytetracycline (OTC), metronidazole (MTZ), and ornidazole (ODZ) overlapped highly with the MOF excitation spectrum (280-325 nm) in the 275-350 nm range, resulting in excitation light competitive absorption and fluorescence quenching [18].

3. The structural characteristics of MOFs and their influence on the fluorescence detection of antibiotics

MOFs are porous crystalline materials formed by the self-assembly of metal nodes (ions/clusters) with organic ligands through coordination bonds. The structural diversity, tunability and functionalization of MOFs form the core basis of fluorescence sensing performance, especially demonstrating outstanding high sensitivity and selectivity in the field of antibiotic detection [19]. The following is an analysis of the correlation between its structural characteristics and fluorescence detection in terms of ligands, metal centers, channels, and topological structures.

3.1. Ligand design: Conjugated systems and functional group regulation

The structural design of organic ligands has a decisive influence on the luminescence performance, detection mechanism and pore characteristics of MOFs. The length, rigidity and functional groups of the ligands jointly regulate the pore size, adsorption capacity, framework stability and fluorescence behavior of the material. Long-chain ligands contribute to expanding pore size and enhancing adsorption capacity for the target [20]. Flexible ligands give the structure dynamic response properties, but often sacrifice crystallinity, while rigid ligands help improve structural stability and form regular channels. In terms of luminescence mechanisms, the π-π* transition of aromatic ligands (such as terephzoic acid and bipyridine) is an important source of luminescence for MOFs, and expanding conjugated systems can enhance fluorescence intensity [1], but when such ligands interact with non-fluorescent antibiotics (e.g., nitrofurans), the antibiotic LUMO orbitals may capture excited-state electrons, It causes PET to cause fluorescence quenching [2]. In addition, functional groups (e.g., -NH_2, -COOH) can modify the pore environment through hydrogen bonding and influence assembly behavior. Amino groups are prone to form hydrogen bonds with antibiotics to induce static quenching and can quench fluorescence due to electron transfer when interacting with metals such as Fe^{3+}. Hydroxyl-modified ligands can suppress the luminescence of tetracycline antibiotics through hydrogen bonding.

3.2. Metal centers: Luminescence properties and paramagnetic quenching

The choice of metal nodes significantly affects the luminescence performance and quenching behavior of MOFs, and the charge, radius, coordination geometry, and electronic configuration together determine the formation of secondary building units (SBUs), thereby regulating the topological structure, pore size, and luminescence properties of MOFs. High-valent metal ions (e.g., Zr^{4+}, Al^{3+}) tend to construct high-coordination number frames to enhance structural stability, while low-valent metal ions are prone to form flexible geometric configurations, which is beneficial for the preparation of luminescent MOFs [18]. Lanthanide metal ions have a large ionic radius, which can expand the material pore size and achieve f-f transition luminescence through the "antenna effect", but their luminescence is highly sensitive to the coordination environment, and changes in coordination number or symmetry can lead to reduced fluorescence. Metronidazole (MTZ) quenches Eu^{3+} luminescence by inducing an internal filtration effect (IFE) through competitive absorption in Eu^{3+}@MOF-253 [21]. On the other hand, paramagnetic metals with unpaired electrons, including Cu^{2+}, can accelerate excited-state decay through spin-orbital coupling and reduce fluorescence efficiency. For example, the paramagnetism of $\{Cu_4(COO)_4(\mu_2\text{-}OH)_2\}$ SBU in Cu-MOFs, although resulting in weaker intrinsic fluorescence, enhances the dynamic quenching effect on antibiotics [2].

3.3. Channels and topological structure: Limiting effects and spatial matching

Pore size, porosity and topology together determine the distribution of adsorption sites and sensing efficiency of antibiotics. In the field of adsorption regulation, larger specific surface area and higher porosity provide more abundant binding sites for antibiotics. When the size of the antibiotic molecule matches the pore size, significant confinement effects occur. For example, Zr-MOF can selectively adsorb small molecule sulfonamide antibiotics using size sieving mechanisms [6]. When the antibiotic enters the pore, it binds to active sites such as carboxyl oxygen and then triggers fluorescence quenching through RET or PET processes. For example, in Cd-MOF, $Cr_2O_7^{2-}$ adsorption triggers the RET effect due to spectral overlap [9]. If the antibiotic is too large to enter the pore, electron transfer may be triggered by surface π-π stacking or electrostatic interaction, but the sensing efficiency of this process is usually lower than that of the in-pore binding mechanism [14]. Topological flexible structures can enhance antibiotic adaptability by dynamically adjusting the pore size through rotation [2]. Topologically rigid MOFs, though highly stable, may have limited dynamic response capabilities [17].

4. Research progress on the detection of different types of antibiotics by MOFs

4.1. Tetracycline antibiotics

Tetracyclines (TCs), such as tetracycline (TC), chlortetracycline (CTC), oxytetracycline (OTC), and doxycycline (DOX), are broad-spectrum antibiotics widely used in livestock and aquaculture. The multiple phenolic hydroxyl and carbonyl groups in its molecular structure specifically bind to MOFs through hydrogen bonds, π-π stacking, etc., providing a molecular recognition basis for fluorescence sensing. Liu et al. [22] synthesized a Tb-MOF with intense green fluorescence for TC sensing and detection. There are multiple hydrogen bond active sites on the surface of TB-MOF that selectively bind to TC and quench the fluorescence of TB-MOF through the internal filtration effect IFE and the energy transfer mechanism of ligands to Tb^{3+} ions. The method has a linear range of 0 to 100 μmol/L and a detection limit of 184 nmol/L, fully verifying the high stability and reusability of MOFs materials. In addition, compared with traditional methods, the MOFs sensor simplifies the pretreatment process and is suitable for rapid field detection of complex matrix samples. For example, in actual samples such as pork and milk, the ratio - colorimetric dual-mode sensor constructed by combining carbon dots (CDs) with MOFs enables dual-mode detection of TC, CTC, OTC and DOX in animal food products through changes in fluorescence intensity and visible colorimetric signals (such as the change of solution color from blue to red), with detection limits as low as the μM level. Even in fat-rich and protein-rich matrices, the sensor shows excellent anti-interference performance, highlighting the practical value of MOFs composites [23].

4.2. Quinolone antibiotics

Quinolones, a class of broad-spectrum antibacterial drugs, mainly including norfloxacin (NOR), ciprofloxacin (CIP), levofloxacin (LVX), and gatifloxacin (GAT), are widely used in human medicine and animal husbandry. Their residues can enter the human body through the food chain, causing problems such as allergic reactions, immunosuppression and genotoxicity [24]. The electronic properties of quinolone antibiotics can precisely align with the optical mechanism structure of MOFs, thereby enabling specific recognition functions. For example, the complex 9 (Tb-MOF) synthesized by Zhao Yue's team [13] showed significant fluorescence quenching effects on GAT and LVX, with detection limits reduced to the micro-molar level. The quenching principle is derived from the energy competition between MOFs and antibiotic molecules, and the material can also effectively distinguish common interferers such as tetracyclines and sulfonamides, highlighting its high selectivity. In addition, the open-channel structure of MOFs promotes the rapid diffusion of antibiotic molecules, with response times typically at the second to minute level, far exceeding the efficiency of traditional chromatographic methods. For example, the host-guest composite developed by Yu's group [25] RhB@TB-dcpcpt achieved multisignal response to quinolone antibiotics by loading luminescent dyes. The sensor was capable of detecting NOR in water samples within 5 minutes, could be reused more than 5 times after simple cleaning, and had a fluorescence intensity retention rate of over 90%.

4.3. Sulfonamide antibiotics

Sulfonamide antibiotics are synthetic antibacterial drugs with para-aminobenzenesulfonamide as the core, in which the hydrogen atom of the amino group can be replaced by various heterocycles to form derivatives such as sulfadiazine (SDZ), sulfamethoxazole (SDM), and sulfamethoxazole (SMX). These antibiotics are structurally diverse and environmentally persistent, making it difficult for traditional detection methods to achieve highly specific identification [26]. Huang Yongqiang's team [27] constructed ratio fluorescence molecularly imprinted probes using zeolite imidazolate backbone material ZF-8 as a carrier for the detection of SDZ in tap water and milk. In the 0-100 μmol/L concentration range, SDZ content was linearly related to the fluorescence intensity of the probe, with a detection limit of 11.23 nmol/L and a relative standard deviation of less than 1.7%. The study shows that the Mofs-based detection platform has significant application value in the rapid screening of sulfonamide residues in environmental water and food, laying the foundation for the development of

efficient and portable detection devices. Yu Xiaoyan [28] synthesized europium-based MOFs (Eu-MOFs) for the detection of SMX and SDM in DMF solutions. When the excitation wavelength is less than 280 nm, sulfonamide antibiotics compete with Eu-MOFs for energy transfer, resulting in significant quenching of the characteristic fluorescence of the material. The sensor has a detection limit as low as 10^{-6} M and maintains high selectivity even in the presence of high concentrations of interfering substances such as other antibiotics or ions, with quenching efficiency exceeding 70%. The method does not require complex pretreatment, responds within 2 minutes, significantly improves detection efficiency, and its high sensitivity is suitable for rapid screening of trace sulfonamide residues in environmental water bodies.

4.4. Nitroimidazole antibiotics

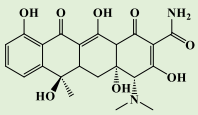
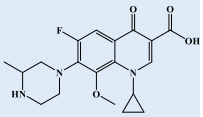
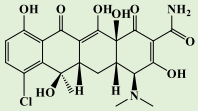
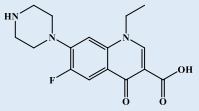
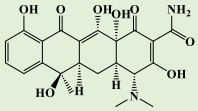
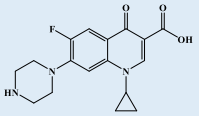
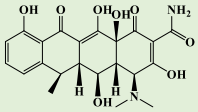
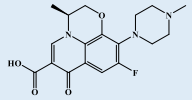
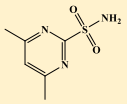
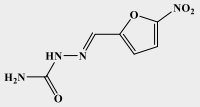
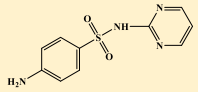
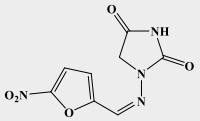
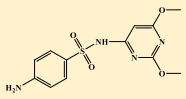
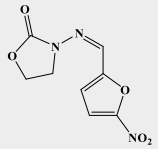
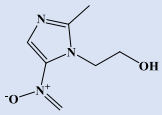
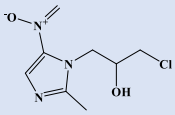
Nitroimidazole antibiotics such as metronidazole (MTZ) and ornidazole (ODZ) are widely used to treat bacterial and protozoan infections. These antibiotics remain stable in the environment and are prone to accumulate through the food chain, posing a potential risk to human health (such as carcinogenicity and drug resistance), so it is crucial to develop highly sensitive detection methods. MOFs have shown significant advantages in the detection of nidazole antibiotics, effectively eliminating complex matrix interference, achieving rapid response, and being recyclable. For example, Liu Yue [21] loaded europium ions (Eu^{3+}) onto an aluminum-based MOF-253 to construct the fluorescence sensor Eu^{3+}@MOF-253 for the detection of MTZ in water environments. The sensor has a detection limit as low as 0.196 μM and a wide linear detection range (0-50 μM). Under the coexistence of 14 interfering substances such as roxithromycin and chloramphenicol, MTZ can significantly quench material fluorescence (with a much higher quenching rate than other antibiotics), confirming its specific recognition ability for MTZ. The sensor was successfully applied to the quantitative detection of MTZ in actual water samples, with a recovery rate of 95% - 102%, indicating its excellent resistance to matrix interference. In addition, the cadmium-based MOF-1 $\{[Cd_2L_1(DMF)_2 \cdot H_2O] \cdot 2DMF\}$ developed by Ji Xiaoxi [29] has a detection limit of 0.1 μM for metronidazole in actual water samples, a response time of less than 2 minutes, and a fluorescence quenching constant (Ksv) as high as 1.47×10^5 M^{-1}. The low-cost synthesis method and excellent repeatability (RSD <2.3%) of MOF-1 support its large-scale application. The material has been successfully applied to the detection of river and medical wastewater samples, with recoveries ranging from 87% to 116%, further confirming the detection reliability of MOFs in complex environments.

4.5. Nitrofuran antibiotics

Nitrofuran antibiotics, such as Nitrofurazone (NFZ), nitrofurantoin (NFT), and furazolidone (FZD), exhibit high toxicity, non-biodegradability, and persistent residual properties [30]. For example, Li Wenqian [2] successfully detected nitrofuran antibiotics NFZ and NFT in aqueous solution systems using fluorescent MOFs (complex 4) synthesized by solvothermal method. At a concentration of 0.1 mM, NFZ or NFT triggered a significant fluorescence quenching effect, with a quenching rate far exceeding that of the other nine antibiotics, confirming the high specificity of the material. The anti-interference experiments showed that common antibiotics such as sulfonamides or tetracyclines had weak interference with the detection, highlighting their suitability in complex real-world samples. In addition, BUT-129 (a methyl-substituted indium MOF) achieved fluorescence quenching efficiency of over 90% in actual water and shrimp samples through the synergistic mechanism of IFE and PET, with detection limits as low as 27-40 ppb, outperforming traditional methods. Experiments showed that BUT-129 maintained high selectivity even in the presence of interfering ions such as Fe^{3+} or $Cr_2O_7^{2-}$, meeting the World Health Organization's standard requirements for screening antibiotic residues in water environments [31].

The types, abbreviations and structural formulas of the antibiotics involved in the full text are listed in Table.1.

Table 1. Summary of the types, abbreviations and structural formulas of the involved antibiotics.

Types of antibiotics	Abbreviation	Full Name	Structural Formula	Types of antibiotics	Abbreviation	Full Name	Structural Formula
Tetracyclines	TC	Tetracycline		Quinolones	GAT	Gatifloxacin	
	CTC	Chlortetracycline			NOR	Norfloxacin	
	OTC	Oxytetracycline			CIP	Ciprofloxacin	
	DOX	Doxycycline			LVX	Levofloxacin	
Sulfonamides	SMX	Sulfamethoxazole		Nitrofurans	NFZ	Nitrofurazone	
	SUL	Sulfadiazine			NFT	Nitrofurantoin	
	SDM	Sulfadimethoxine			FZD	Furazolidone	
Nitroimidazoles	MTZ	Metronidazole		Nitroimidazoles	ODZ	Ornidazole	

5. Future development direction

5.1. Optimization and innovation of MOFs bulk materials

At present, MOFs still face challenges such as insufficient stability and limited selectivity in fluorescence detection. In the future, there will be a need for breakthroughs in areas such as enhancing material stability, precisely regulating fluorescence performance, and developing novel structures. By introducing high-valent metal ions (such as Al^{3+}, Zr^{4+}) or hydrophobic ligands, the chemical stability of MOFs in the aqueous phase and complex matrices is enhanced to avoid signal distortion caused by structural collapse. Design MOFs with dual emission characteristics or ratio fluorescence responses to reduce environmental interference through self-calibration mechanisms and improve detection reliability. For example, the dual emission design of Al-MOFs can be constructed into ratio fluorescence sensors that can detect target contaminants with high sensitivity and selectivity [8]. Explore new materials such as 2D-MOFs to enhance sensitivity and response speed to trace antibiotics by taking advantage of their high specific surface area and efficient energy transfer properties [4].

5.2. Construction of multi-technology/material synergistic systems

The limitations of a single MOFs can be overcome through a composite strategy. Combining molecularly imprinted polymers (MIPS) to construct specific recognition sites within MOFs channels significantly enhances antibiotic selectivity. Gan et al. developed a fluorescence sensor based on fluorescent Eu-MOFs for the visualization and rapid detection of TC [32]. Loading quantum dots or rare earth nanoparticles and amplifying the signal with FRET to lower the detection limit [8]. Develop "fluorescence-electrochemical" dual-mode sensors, improve data reliability through cross-validation, and expand multi-target synchronous detection [3].

5.3. Expansion and implementation of practical application scenarios

In response to the urgent needs of environmental monitoring, food safety and clinical diagnosis, future research should focus on integrating MOFs sensing technology into miniaturized, portable devices. Loading MOFs powder onto test strips, microfluidic chips, or smartphone integrated platforms for rapid field detection, such as UST-545 and UST-546, which have good selectivity, sensitivity, and detection performance when detecting these types of target analytes [16]. Anti-interference MOFs probes are designed for real samples such as food and environmental water samples, and the target is enriched through the pretreatment module to improve the signal-to-noise ratio [4]. Standardize and scale up production, establish a quality control system for MOFs synthesis, develop low-cost macrofabrication methods, and promote the commercialization of sensors [33].

6. Conclusions

Antibiotic residues pose a serious threat to the ecological environment and human health. It is important to develop rapid, sensitive and portable detection technologies. MOFs, with their high specific surface area, tunable pore structure, excellent luminescence performance and flexible functional design, have shown significant advantages in antibiotic fluorescence detection. This paper systematically reviews the luminescence mechanism, sensing principle, structure-performance relationship of MOFs for fluorescence detection of antibiotics and the research progress in the detection of tetracyclines, quinolones, sulfonamides, nitroimidazoles, nitrofurans and other antibiotics. MOFs sensors have shown good applicability in actual samples (such as water, milk, pork, shrimp, medical wastewater, etc.), with low detection limits, high selectivity and strong anti-interference ability. Some materials can also be visualized for rapid detection and reuse, showing great potential for field application. Although technology has made progress in antibiotic detection, it still faces challenges such as insufficient stability, matrix interference and limited multi-component detection capabilities. In the future, the stability of MOFs should be enhanced, proportional or multimodal sensing strategies should be developed to improve accuracy, and integration with portable devices should be promoted for real-time monitoring. Overall, MOFs fluorescence sensing technology provides an effective means for the rapid detection of antibiotic residues and has broad application prospects.

References

[1] Zhang Songlin. Sensitive detection of tetracycline by surface-induced fluorescence enhancement visualization of metal-organic skeleton [D]. North China Electric Power University, 2022.

[2] Li Wenqian. Construction of fluorescent metal-organic frameworks and their recognition performance for bioactive small molecules [D]. North University of China, 2024.

[3] Wang Guixin. Research on the performance of metal-organic frameworks and their fluorescent probes in pollutant detection [D]. Suzhou University of Science and Technology, 2023.

[4] Li Guanghua. Research on Antibiotic optical Sensing Based on Porous Organic Framework materials [D]. Hebei Medical University, 2024.

[5] Wang Guojiao. Research on regulated synthesis of stable MOFs and fluorescence-sensing Antibiotic performance [D]. Shanxi Normal University, 2022.

[6] Fan Yingyi. Construction of MOFs based on Nitrogen-containing tetracharboxylic acid ligands and research on adsorption and fluorescence sensing properties [D]. Wuhan Textile University, 2024.

[7] Lu Yukuo. Construction and properties of polycarboxylic acid metal-organic frameworks based on amide/amino groups [D]. Northwestern University, 2021.

[8] Heine J, Muller-Buschbaum Klaus. Engineering metal-based luminescence in coordination polymers and metal-organic frameworks [J]. Chemical Society Reviews, 2013, 42(24):9232-9242.

[9] Wang K, Bai X, Zhao X, et al.Highly sensitive fluorescence detection of nitrofurazone and nitrofurantoin in milk and honey using a hydrostable Cd(II) metal-organic framework [J]. Journal of Molecular Structure, 2023.

[10] Wang Jinjin. Synthesis of metal-organic frameworks based on 5,5' -benzothiadiazole-4, 7-diisophthalic acid and fluorescence sensing and magnetic properties [D]. Jiangxi University of Science and Technology, 2024.

[11] Xie Ruirui. Fluorescence sensors based on metal-organic frameworks and their applications in analysis [D]. Southern Medical University, 2021.

[12] Zhang Xiaoyu. Research on Constructing Crystalline Materials with Polycyclic nitrogen-containing ligands for fluorescence detection of pollutants [D]. Changchun University of Science and Technology, 2023.

[13] Zhao Yue. Research on Luminescent metal-organic framework materials constructed with polycarboxylic acid ligands and their fluorescence recognition properties [D]. Liaocheng University, 2023.

[14] Wen Yangxin. Construction of Novel porous Materials Based on Post-modification strategies and their detection and separation properties [D]. Shandong Normal University, 2022.

[15] Daly B, Ling J, De Silva A P .Current developments in fluorescent PET (photoinduced electron transfer) sensors and switches [J]. Chemical Society Reviews, 2015, 44.

[16] Hao J N, Yan B.A dual-emitting 4d–4f nanocrystalline metal–organic framework as a self-calibrating luminescent sensor for indoor formaldehyde pollution [J]. Nanoscale, 2016, 8(23):12047-12053.

[17] Wang Pengmin. Construction and fluorescence properties of materials based on diquinoline ligand framework [D]. Huazhong University of Science and Technology, 2023.

[18] Xian Guoxuan. Research on Synthesis, structure and fluorescence Sensing properties of MOFs crystalline materials Based on flexible polycarboxylic acid ligands [D]. Liaocheng University, 2021.

[19] Wan Xiaoyu. Research on Metal ion fluorescence Sensing Properties of MOFs Crystalline Materials Based on amino and iminocarboxylic acid ligands [D]. Liaocheng University, 2022.

[20] Yang Yujie, Zhang Jianxu, Wang Wenmeng, et al. Advances in applications of metal-organic frameworks (MOFs) [J]. Journal of Changchun University of Science and Technology (Natural Science Edition), 2025(2).

[21] Liu Yue. Preparation of fluorescence sensor Based on Aluminum-based MOFs and its High Sensitivity detection performance for contaminants [D]. Anhui University, 2024.

[22] A X L, B Q M A, A X F, et al.A recycled Tb-MOF fluorescent sensing material for highly sensitive and selective detection of tetracycline in milk[J]. Microchemical Journal, 2021.

[23] Wang Chunyan. Dual-mode detection of tetracycline in animal food based on carbon dot, metal-organic framework fluorescence sensor ratio colorimetry [D]. Northwest A&F University, 2023.

[24] Wang K, Bai X, Zhao X, et al. Highly sensitive fluorescence detection of nitrofurazone and nitrofurantoin in milk and honey using a hydrostable Cd(II) metal-organic framework[J]. Journal of Molecular Structure, 2023.

[25] Yu M, Xie Y, Wang X, et al.Highly Water-Stable Dye@Ln-MOFs for Sensitive and Selective Detection toward Antibiotics in Water[J]. ACS Applied Materials & Interfaces, 2019, 11(23).

[26] Shen Dongjun, Zheng Xuan, Liu Yuzhen, et al. Research progress on pollution status and analytical methods of sulfonamide antibiotics in soil [J]. Chemical World, 2024, 65(5):277-283.

[27] Huang Yongqiang, Ming Qin, Huang Weihong, et al. Determination of sulfadiazine by ratio fluorescence blotting probe based on metal-organic framework materials [J]. Laboratory for Analysis, 2024, 43(6):767-773.

[28] Yu Xiaoyan. Design and synthesis of luminescent MOFs and their fluorescence sensing properties [D]. China Three Gorges University, 2025.

[29] Ji Xiaoxi. Construction of transition metal-Organic skeleton sensors and fluorescence recognition of Nitro antibiotics [D]. Shenyang University of Chemical Technology, 2022.

[30] Sun. Preparation of metal-organic framework materials and their fluorescence recognition of nitro antibiotics [D]. East China Normal University, 2021.

[31] Wang B, Yan B. A turn-on fluorescence probe Eu3+ functionalized Ga-MOF integrated with logic gate operation for detecting ppm-level ciprofloxacin (CIP) in urine [J]. Elsevier, 2020.

[32] Gan Z, Hu X, Xu X, et al. A portable test strip based on fluorescent europium-based metal-organic framework for rapid and visual detection of tetracycline in food samples [J]. Food Chemistry, 2021, 354(3):129501.

[33] Huang Jincheng, Liu Huakai, and Su Peiyang. A benzothiadiazol-based metal-organic framework and its detection of Nitrofurazone [J]. Guangdong Chemical Industry, 2024, 51(24):114-117.