Public Health and Environment 2026, 2(1), 27–53.
https://doi.org/10.70737/k2xq0w66

Review

Metal-Organic Framework–Hydrogel Composites for Next-Generation Biosensing: Advances in Optical Detection of Environmental Pollutants

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CITATION

Li H., Liu Y., Li R., Zhou X., Liu J. Metal-Organic Framework–Hydrogel Composites for Next-Generation Biosensing: Advances in Optical Detection of Environmental Pollutants. Public Health and Environment. 2026, 2(1): 27–53. https://doi.org/10.70737/k2xq0w66

ARTICLE INFO

Received: 23 December 2025
Accepted: 29 January 2026
Available online: 9 February 2026

Abstract: Metal-organic framework–hydrogel (MOF–hydrogel) composites, leveraging their distinctive structural and functional advantages, offer an ideal platform for developing a new generation of optical biosensing technologies for environmental pollutants detection. While conventional analytical methods provide high accuracy, the reliance on bulky instruments and complex operational procedures limits their applicability. This review focuses on design strategies of such composite materials and recent advances in their application to optical biosensing of environmental contaminants. Through approaches such as *in situ* growth and direct mixing, the structural tunability and catalytic/luminescent properties of MOFs are effectively integrated with the three-dimensional hydrophilic networks and stimuli-responsive characteristics of hydrogels, resulting in synergistic functionality. The review systematically outlines the multifunctional roles of MOFs in sensing, including as luminophores, catalysts, signal modulators, and carriers. Representative applications in detecting pathogenic microorganisms, antibiotics, heavy metal ions, and pesticide residues are categorized and discussed, demonstrating the notable advantages of these biosensing assays in terms of sensitivity, selectivity, and field applicability. Finally, future challenges and research directions are outlined, including improving the environmental stability of materials, developing methods for simultaneous multi-target detection, advancing the portability and intelligence of sensing systems, and expanding the range of applications in environments. MOF–hydrogel composites hold strong promise as a robust material platform for the development of high-performance, field-deployable water quality sensing technologies.

Keywords: metal-organic frameworks; hydrogels; optical biosensing; environmental contaminants; detection

1. Introduction

Over recent decades, the combined pressures of rapid population growth and industrialization have rendered environmental pollution a critical global challenge, posing significant threats to ecosystem integrity and public health [1]. Many pollutants, such as heavy metals, organic compounds, and toxic gases present in water and air, are associated with significant health risks [2,3]. Chromatography and its hyphenated techniques serve as the primary methods for the analysis of environmental contaminants. However, chromatographic techniques typically require expensive instrumentation, complex sample pretreatment, and lengthy analysis times. Consequently, there is a critical need for new sensing technologies that can address these limitations by offering high sensitivity, rapid response, user-friendly operation, and capabilities for *in situ*, real-time, and continuous monitoring.

Biosensing presents itself as a highly promising solution, offering distinct advantages such as cost-effectiveness, operational simplicity, rapid response, high sensitivity, and excellent portability [4–7] (**Figure 1a**). Based on the functional sensing components employed, biosensing encompasses multiple modalities, including enzyme-, antibody-, nucleic acid-, and whole cell-based approaches. Biosensing has been successfully applied to detect heavy metals, microorganisms, antibiotics, pesticides, and other contaminants in aqueous environments [8–11]. Moreover, the integration of biosensing with environmental epidemiology has enabled real-time monitoring of pollutant concentrations, such as pharmaceuticals, in diverse environmental media [12]. Significant efforts are underway to evaluate the potential of this technology to monitor diverse contaminants across multiple environmental matrices.

In recent years, metal-organic frameworks (MOFs) have attracted considerable interest in the research community (**Figure 1b**). MOFs are crystalline materials consisting of metal ions and organic ligands connected via coordination bonds, giving rise to extended, often porous, network architectures [13–15]. These materials exhibit high crystallinity alongside tunable surface area, porosity, and pore size, as well as remarkable catalytic activity, including the ability to mimic natural enzymes such as peroxidases and oxidases. This tunability arises from their highly designable architecture, as the morphology, structure, and functionality of MOFs can be precisely tailored through the modular selection of metal ions and organic ligands. These combined properties position MOFs as promising candidates for diverse applications such as sensing, catalysis, and gas storage, driving extensive interdisciplinary research [15,16].

Hydrogels are three-dimensional polymer networks characterized by high water content, swellability, and stimuli-responsive properties, which impart deformability and softness similar to those of elastic solids [17] (**Figure 1c**). Building on this, the porous hydrogel network not only provides a uniform, stabilizing matrix for MOF dispersion but also enables synergy between its soft-matter properties and specific MOF functions, such as catalysis and adsorption [18,19]. This integration allows for the precise tuning of key material properties, including porosity, release kinetics, and mechanical strength. Thus, MOF–hydrogel composites pave the way for next-generation biosensing platforms, offering a versatile and potent solution for monitoring environmental pollutants with enhanced performance.

This review summarizes recent advances in applying MOF–hydrogel composites to optical biosensing, specifically for environmental pollutant detection. This review systematically examines the design strategies for optical sensing systems utilizing MOF–hydrogel composites and evaluates their representative applications in detecting diverse environmental contaminants, including pathogens, organic pollutants, heavy metals, and pesticide residues. Finally, building on the progress and limitations discussed, we outline future research directions and highlight the critical challenges that must be overcome to translate the potential of these composites into robust, real-world environmental monitoring solutions.

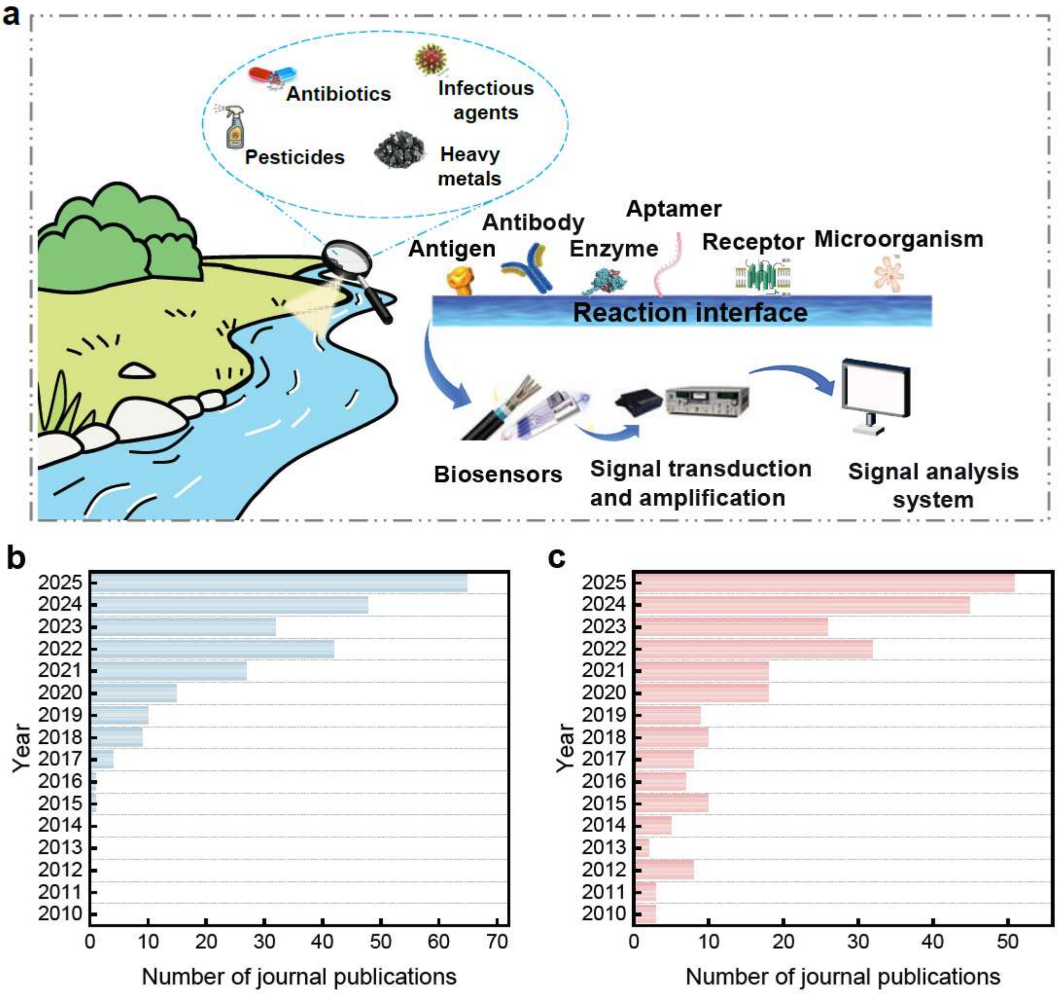

Figure 1. Research Landscape of Biosensing for Environmental Pollutants: A Technology Overview and Development Trends of Key Materials (MOF–hydrogel composites). **(a)** Biosensing for monitoring pollutants from diverse environmental sources; **(b)** Annual growth in publications on MOF–based biosensing for environmental pollutant detection (2010–2025). Data were obtained from the Web of Science database using the following keywords: "MOF", "Biosensing" and "Environment"; **(c)** Annual publication trend on hydrogel-based biosensing for the detection of environmental pollutants (2010–2025). Data were retrieved from the Web of Science database employing the keywords "Hydrogel", "Biosensing" and "Environment".

2. Engineering Strategies for the Formation of MOF–Hydrogel Composites

2.1. Types and Functions of Hydrogel Matrices

A variety of polymers have been used to synthesize hydrogel–based sensors, in which polymer chains are cross-linked via covalent bonds or noncovalent interactions to form three-dimensional networks [20]. These polymers serve dual purposes: as a base material to enhance mechanical properties, or as functional components that impart unique sensing capabilities by leveraging their inherent chemical, biological, or physical traits. These capabilities include stimuli-responsiveness [21], chemical detection [22,23], conductivity [24,25], and self-healing [25–28]. In particular, synthetic polymers such as polyacrylamide (PAM), polyvinyl imidazole (PVI), polyvinyl alcohol (PVA), polyethylene glycol (PEG), and polyvinyl pyrrolidone (PVP) are frequently employed as base materials or functional components in hydrogel sensing applications [29].

2.1.1. Natural Polymers

Natural polymers, such as polysaccharides, alginate, proteins, and DNA, are extensively employed in sensing hydrogels owing to their abundant functional groups [30], distinctive physicochemical properties, and inherent advantages including biocompatibility (i.e., a compatible interface with encapsulated biorecognition elements) [31], environmental responsiveness, bioadhesion, and high swelling capacity. These attributes collectively render natural polymers preferable to synthetic ones for many sensing applications [32–34].

Among these, polysaccharides are characterized by exceptional hydrophilicity and high water-retention capacity, enabling them to effectively replicate the hydrated microenvironment of natural tissues [35–37]. The combination of these features with tunable physicochemical properties and high biocompatibility enables polysaccharide-based hydrogels to serve as highly suitable platforms for sensing [38]. Chen et al. [39] developed an agarose hydrogel-based colorimetric sensor utilizing a single-iron-site nanozyme for the point-of-care detection of glucose via a glucose oxidase–nanozyme cascade reaction. Zou et al. [40] developed a dual-enhanced enzyme cascade hybrid system based on an agarose hydrogel for the construction of a portable colorimetric urea sensor. Li et al. [41] developed a DNA tweezer-actuated nanozyme–enzyme hybrid cascade system based on a sodium alginate hydrogel for the construction of a portable colorimetric sensor for carbamate pesticides.

Alginate (ALG), a natural ionic polysaccharide derived from brown algae, has been extensively employed in food processing, biomedicine, and water treatment fields owing to its excellent biocompatibility, favorable biodegradability, and inherent non-toxicity [42,43]. The widespread application of sodium alginate stems from its capacity to form gel networks in the presence of divalent cations (M^{2+}) under extremely mild conditions. Specifically, the strong specific interactions between M^{2+} and the guluronic acid residue blocks in ALG drive the gelation process, thereby constructing the cross-linked junction zones termed “egg-box” structures.

Owing to their tunable structure and functionality, protein hydrogels have emerged as promising candidates for sensor applications. For instance, Hu et al. [44] integrated protein hydrogels with a temperature-sensitive polymer to achieve controlled adsorption and release of trace uranyl ions from seawater. Gogurla et al. [45] incorporated hydrated melanin nanoparticles into protein hydrogel–elastomer hybrids to develop flexible optoelectronic devices for dopamine detection. In another study, Cai et al. [46] combined two-dimensional photonic crystals with Concanavalin A protein hydrogels to construct an optical sensor for detecting microorganisms in aqueous environments.

Pure DNA hydrogels are formed solely through non-covalent interactions, namely DNA base pairing and chain entanglement. The inherent bioaffinity and structural programmability of DNA hydrogels render them highly suitable for applications in biomolecule detection, environmental monitoring, and point-of-care diagnostics [47–49].

2.1.2. Synthetic Polymers

Synthetic polymers such as PVA, PEG, and PAM possess desirable mechanical strength, flexibility, selective chemical reactivity, and controllable molecular structure suitable for sensors and actuators. PVA is a polymer utilized for its unique mechanical properties, biocompatibility, and biodegradation performance [50–54]. Its abundant hydroxyl groups allow chemical modifications on PVA polymer chains. In addition, the cross-linking of PVA can be achieved either by chemical or physical cross-linking. Because of excellent solubility and ultrahigh absorbance, PVA has been used as a humidity sensor. In addition to humidity [55–57], PVA-based hydrogels have been reported in pH and metal cation sensing [58–60]. Among metal cation sensors, photonic crystal sensors composed of PVA-based hydrogels have been used for the detection of heavy metals [53,61,62]. It has been reported that PVA hydrogel can be used as a glucose sensor [63,64]. The mechanical strength and flexibility of PVA hydrogel were improved for synthesizing pressure and strain sensors for motion detection [65–68]. PEG is another synthetic polymer widely used in biomedical applications. For decades, researchers have explored its potential for application as a hydrogel. Similar to PVA, PEG hydrogels have also been developed for the sensing of chemical substances, including the detection of environmental pollutants [69–71].

Compared to PVA and PEG, PAM hydrogels are widely utilized in biosensing, because of their excellent biocompatibility and well-defined protocols to fabricate robust platforms with desirable mechanical and physiological performances. In terms of molecular recognition, PAM hydrogels can serve as an excellent immobilization matrix. Tian et al. [72] developed a smart hydrogel grating sensor based on PAM, enabling highly sensitive and selective real-time detection of Pb^{2+} in water, with a detection limit as low as 10^{-9} M and a rapid response time of 2 minutes, thereby providing a powerful new approach for real-time and continuous monitoring of heavy metal contamination in environmental water bodies (**Figure 2a**). Li et al. [73] developed a dual-mode sensor based on PAM hydrogel embedded with upconversion nanoprobes, enabling highly sensitive and selective visual detection of the antibiotic amikacin (AMK) in environmental water bodies and biological samples, with a detection limit as low as 1.3 nM and a rapid response within 15 minutes. This provides a reliable new approach for the high-precision and portable monitoring of drug residue pollution (**Figure 2b**). Zhang et al. [74] constructed a colorimetric sensing array based on a frost-resistant double-network hydrogel composed of polyvinyl alcohol/polyacrylamide/lithium chloride (PVA/PAM/LiCl), enabling the accurate identification of four common foodborne pathogens in low-temperature cold-chain environments (4 °C and −20 °C) within 24 hours, thereby providing an innovative and reliable solution for food safety monitoring in cold-chain systems (**Figure 2c**). Additionally, recognition elements such as peptides, proteins, or antibodies can be effectively immobilized within PAM networks, enabling the development of highly selective biosensing for specific environmental pollutants. Wang et al. [75] developed a responsive photonic hydrogel biosensor based on poly(*N*-isopropylacrylamide-*co*-acrylamide) functionalized with penicillinase, enabling highly sensitive and selective visual detection of penicillin G in water with a response time within 30 minutes and excellent recyclability (usable for at least 50 cycles) (**Figure 2d**). This provides a stable, repeatable, and operationally simple new method for detecting β-lactam antibiotic residues in aqueous environments.

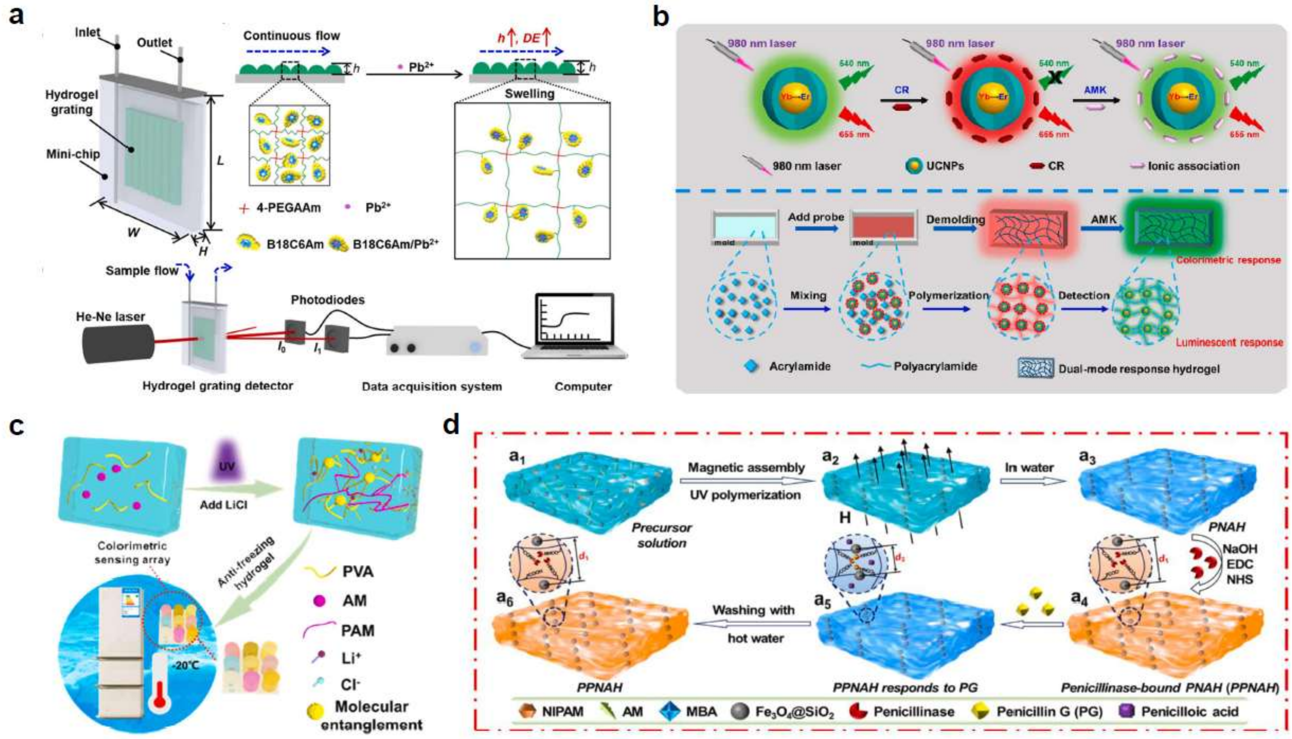

Figure 2. PAM hydrogel biosensing for environmental pollutants detection. **(a)** Real-time continuous-flow hydrogel grating detector for Pb^{2+} (Reprinted and adapted with permission from [72], Elsevier Science, 2023); **(b)** Multifunctional dual-mode hydrogel nanosensor for sensitive, background-free amikacin detection (Reprinted and adapted with permission from [73], Elsevier Science, 2026); **(c)** Frost-resistant hydrogel colorimetric array for foodborne pathogen detection in cold chain (Reprinted and adapted with permission from [74], Elsevier Science, 2025); **(d)** Penicillinase-modified PNIPAM-based hydrogel biosensor with high recyclability for penicillin G detection (Reprinted and adapted with permission from [75], Elsevier Science, 2024).

2.2. Types and Functions of MOF Materials

In optical biosensing, MOFs fulfill distinct functional roles in signal generation and transduction. They may act as: (i) intrinsic luminophores (e.g., lanthanide MOFs), producing direct photoluminescence; (ii) catalytic nanozymes, driving chromogenic reactions for colorimetric readouts; (iii) signal modulators, participating in energy transfer processes (e.g., fluorescence resonance energy transfer) to quench or enhance fluorescence; or (iv) host carriers, encapsulating guest molecules for selective recognition and sensing. This functionality-oriented categorization directly links the structural and compositional design of MOFs to their practical performance in optical sensing, providing a clear framework for the rational development of integrated and high-performance sensing platforms. This section provides a systematic review of MOF–based biosensing strategies, encompassing their functional roles, material design, synthesis methods and analytical applications (**Table 1**).

Table 1. Multifunctional MOFs in biosensing assays for environmental contaminants detection.

Functional Roles	MOF-Based Material	Preparation Method	Category	Analyte	Reference
Luminophores	CDs@ZIF–8	Direct synthesis	Modified MOF	Pb^{2+}	[76]
Luminophores	PCN–222	Direct synthesis	Pristine MOF	Chloramphenicol	[77]
Luminophores	MOF–808@ZIF–Eu	Direct synthesis	Pristine MOF	Tetracyclines	[78]
Luminophores	NH_2–MIL–53	Direct synthesis	Pristine MOF	Tetracyclines	[79]
Luminophores	Zr–MOF	Direct synthesis	Modified MOF	Pyrethroid fungicide	[80]
Catalysts	PCN–224 @AuPtPd@HRP@Aptamer	Post-synthetic modification	Modified MOF	Bacteria	[81]
Catalysts	Apt–NiCoFe–MOF–74	Post-synthetic modification	Modified MOF	Tetracyclines	[82]
Catalysts	MOF@Arg0.25@His0.25	Post-synthetic modification	Modified MOF	Aflatoxin	[83]
Catalysts	ZrFe MOF	Co-precipitation	Pristine MOF	Ampicillin	[84]
Catalysts	MOF–Pt@Cu	Post-synthetic	Modified MOF	Salmonella	[85]
Catalysts	AA@ZIF@Paper	Direct synthesis	Modified MOF	Organophosphorus Pesticides	[86]
Signal modulators	CDs@ZIF–8	Direct synthesis	Modified MOF	Pb^{2+}	[76]
Signal modulators	PCN–222	Direct synthesis	Pristine MOF	Chloramphenicol	[77]
Signal modulators	Eu–MOF	Co-precipitation	Pristine MOF	Ciprofloxacin/ Chloramphenicol	[87]
Signal modulators	PCN–224 @AuPtPd@HRP@Aptamer	Post-synthetic modification	Modified MOF	Bacteria	[81]
Signal modulators	UiO–66–NH_2	Co-precipitation	Pristine MOF	Hg^{2+}	[88]
Carriers	Ce-MOF@MCA	Post-synthetic modification	Modified MOF	Oxytetracycline	[89]
Carriers	Ru@MOF	Direct synthesis	Modified MOF	Chloramphenicol	[90]
Carriers	Zr–UiO–66–NH_2	Direct synthesis	Modified MOF	Penicillin	[91]
Carriers	Ab-Au/Ir@Cu/Zn–MO	Post-synthetic modification	Modified MOF	Staphylococcus aureus	[92]
Carriers	NU–902	Direct synthesis	Pristine MOF	Chloramphenicol	[93]

2.3. Construction Strategies for MOF–Hydrogel Composites

The preparation methods exert a decisive influence on the properties and applications of MOF–hydrogel composites, as they govern the dispersion behavior of MOFs, the preservation of their intrinsic structures, and the morphological characteristics of the resultant products. Meanwhile, the interfacial compatibility between MOFs and hydrogel matrices requires further enhancement through diverse strategies (e.g., crosslinking modification or hydrogel bonding). In this section, three typical methods commonly employed for fabricating MOF–hydrogel composites are systematically introduced, namely *in situ* growth, simultaneous generation, and direct mixing of MOFs with hydrogels, as illustrated in **Figure 3**.

2.3.1. *In Situ* Growth Methods

The *in situ* growth methods aim to directly fabricate MOF architectures within hydrogel substrates. Specifically, hydrogel matrices are first prepared, followed by the introduction of metal salts into the aqueous solution to ensure the full dispersion and subsequent immobilization of metal ions onto the hydrogel networks. Organic ligands are then incorporated to coordinate with the metal ions, ultimately yielding the desired MOF–hydrogel composites, as illustrated in **Figure 3a**(i). In particular, metal ion-crosslinked hydrogels are distinctly promising for the *in situ* growth of MOF architectures, as MOFs can be formed using the metal ions at the crosslinking sites as central metal ions, as illustrated in **Figure 3a**(ii). Composites synthesized via the *in situ* method exhibit excellent flexibility and moldability, with MOF crystals uniformly dispersed throughout the hydrogel networks. Moreover, these MOF–hydrogel composites display superior performance including high water retention capacity, favorable porosity, and good cytocompatibility, while well preserving the inherent porous architecture of pristine MOF materials.

ALG hydrogels (especially sodium alginate) are the most widely utilized hydrogel matrices for the *in situ* fabrication of MOF–hydrogel composites, owing to the feasibility of metal-ion cross-linking and the broad selection of metal ions applicable for gel formation. In the presence of organic ligands, MOF architectures can be fabricated *in situ* within ALG hydrogel networks. Leveraging the two *in situ* protocols illustrated in **Figure 3a**, researchers have successfully prepared a series of MOF/ALG hydrogel composites [94–97]. For instance, Li et al. [98] fabricated a series of ALG@ZIF–67 hydrogels via *in situ* growth of ZIF–67 on ALG hydrogels, and the resulting hydrogel composites were employed for the adsorption of Cu(II) from aqueous solutions. In this study, $CaCl_2$–crosslinked ALG hydrogels were first prepared and subsequently transferred to a solution containing cobalt metal salts and 2–methylimidazole (organic ligand). The *in situ* formation of ZIF–67 within the hydrogel networks ultimately yielded the ALG@ZIF–67 hydrogel composites.

To fabricate MOF–hydrogel structures via the *in situ* process illustrated in **Figure 3a**(ii), Lee et al. [99] prepared Cu–MOF–alginate (Cu–MOF–Alg) composite beads using this protocol for the efficient removal of dissolved salt ions from seawater under energy-free conditions. MOFs were successfully synthesized *in situ* within the pre-formed Cu-coordinated alginate matrix in the presence of organic ligands, yielding Cu–MOF–Alg beads capable of efficiently removing water-soluble salt ions from various types of solutions. Notably, the macroscopic morphology of MOF–hydrogel composites can be tailored by regulating the shape of the precursor hydrogel.

2.3.2. Simultaneous Formation of MOF and Hydrogel

In these methods, hydrogel precursors and MOF metal salts are simultaneously introduced into the reaction system, enabling the concurrent formation of MOF architectures and cross-linking of hydrogel networks — processes also referred to as the one-step methods. As illustrated in **Figure 3b**, the MOF–hydrogel composites form as soon as the chelation process occurs in the presence of organic ligands. Alanazi et al. [100] fabricated aptamer-functionalized metal–organic framework hydrogel beads (Apt–MOF@hydrogel beads) via the simultaneous formation strategy, enabling the colorimetric detection of ochratoxin A (OTA) in rice samples with high specificity and sensitivity. The composites were synthesized via an *in situ* coordination-facilitated ionic gelation approach. In this method, two precursor solutions were prepared: one containing chitosan, OTA–specific aptamer, and Cu^{2+} ions, and the other consisting of gallic acid in an alkaline medium. Upon dropwise addition of the former solution to the latter, ionic cross-linking-induced gelation of chitosan and coordination-driven formation of Cu–GA MOF crystals proceeded concurrently within the forming hydrogel networks. This one-pot process enabled the homogeneous embedding of MOF crystallites and aptamer molecules into the chitosan hydrogel matrices, yielding stable composites with integrated peroxidase-mimetic activity and molecular recognition capability for sensitive target detection. According to publications on MOF–hydrogel composites prepared via the simultaneous formation method, only MOF structures that can be rapidly formed in aqueous solutions at room temperature are suitable for this protocol. Consequently, numerous researchers prefer to fabricate MOF–hydrogel composites using the direct mixing method, which will be discussed in the following section.

2.3.3. Direct Mixing Methods

To fabricate MOF–hydrogel composites via the direct mixing methods, pre-synthesized MOF crystals are first prepared and mixed with hydrogel precursors according to a specific formulation. Following cross-linking reactions, the MOF structures are immobilized within the hydrogel matrices, as illustrated in **Figure 3c**. The direct mixing methods are widely utilized for the fabrication of MOF–hydrogel composites owing to their operational simplicity, mild reaction conditions, and ease of controlling the content and structures of MOFs. Notably, these methods serve as the primary approach for constructing MOF–hydrogel biosensing platforms, particularly those designed for the detection of environmental pollutants.

Given their procedural simplicity, MOF–hydrogel composites are predominantly fabricated via direct mixing methods; representative MOFs employed include ZIFs, UiO series, MIL–100(Fe), Ni–MOFs, and HKUST–1 [101–104]. Cao et al. [105] fabricated an OPA–Au bowl@Cu–MOF composite hydrogel sensor via a stepwise embedding and cross-linking approach, a modified variant of the direct mixing methods. In their work, pre-synthesized Au-nanobowl@Cu–MOF core–shell nanoparticles were first dispersed uniformly in a sodium alginate solution. This mixture was subsequently cross-linked with calcium ions in the presence of o-phthalaldehyde (OPA), a process that simultaneously solidified the hydrogel and immobilized the functional components within its three-dimensional network. The resulting composite hydrogel was employed for the highly selective detection of putrescine in food and environmental samples, leveraging a Schiff–base reaction coupled with Cu–N coordination-enhanced SERS signaling.

Direct mixing methods readily yield multifunctional, stimuli-responsive MOF–hydrogel composites through a single integrated preparation step. Using these methods, MOFs are encapsulated within a stimuli-responsive hydrogel matrix. The presence of target molecules triggers a structural transition in the gel, releasing the MOFs and subsequently activating their signal output, thereby facilitating sensitive target detection. Sun et al. [106] constructed a stimuli-responsive colorimetric aptasensor by simply mixing hemin-encapsulated MOF with fumonisin B1 (FB1) –responsive DNA hydrogel. The detection is achieved through target-induced hydrogel decomposition, which releases the MOF and restores its peroxidase-like activity to catalyze the oxidation of tetramethylbenzidine (TMB) by hydrogen peroxide (H_2O_2), producing a blue color signal proportional to the concentration of FB1. This method enables highly sensitive detection of FB1, with a linear range of 0.05–100 ng/mL and a detection limit of 0.024 ng/mL. In addition, MOFs can provide abundant multiple binding sites for a variety of small-molecule drugs and biomacromolecules through chemical conjugation, physical encapsulation, and surface coordination interactions [107,108]. Therefore, the direct mixing strategy presents a versatile and efficient route for fabricating multifunctional platforms from MOF–hydrogel composites.

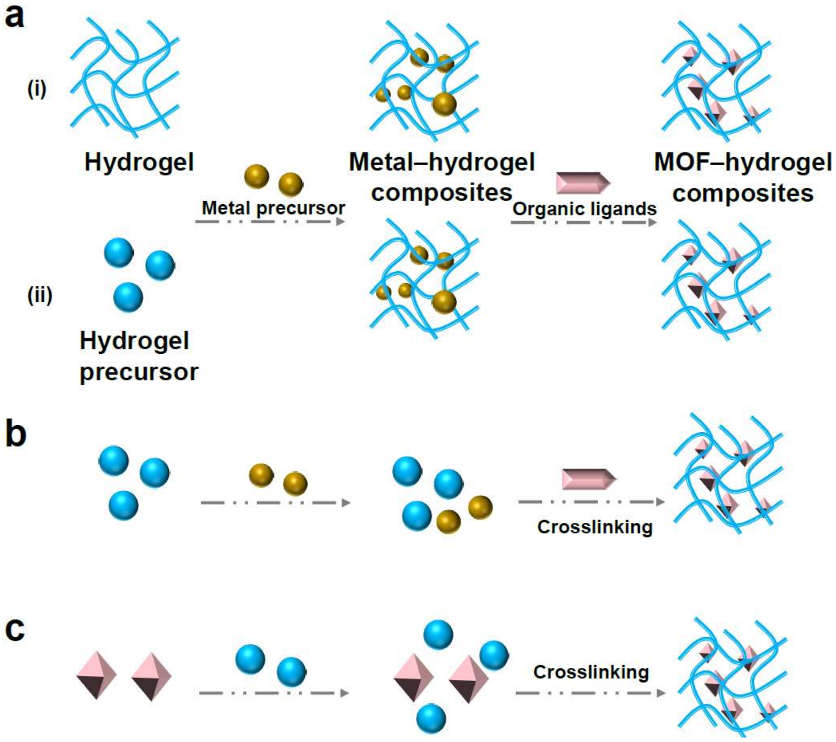

Figure 3. Schematic illustrations for the synthesis of MOF–hydrogel composites using **(a)** *in situ* growth method, **(b)** simultaneous generation of MOF and hydrogel, and **(c)** direct mixing methods.

3. Applications in Environmental Contaminants Detection

MOF–hydrogel composites integrate the dual advantages of MOFs and hydrogel materials, forming high-performance nanocomposites with broad application prospects in the field of biosensing. This review focuses on their applications and research progress in this field, with particular emphasis on the detection of environmental pollutants.

3.1. Detection of Infectious Agents Using MOF–Hydrogel Composites

Bacteria, viruses, and parasites are key biological contaminants that pose a serious risk to human health and are therefore a major focus in environmental monitoring. Their threat arises from high pathogenicity, environmental persistence, and resistance to disinfection. Primarily disseminated via the fecal-oral route from sources such as sewage and agricultural runoff, these pollutants, particularly viruses, present a formidable challenge due to their ability to remain infectious even at high dilution and infiltrate deep groundwater. This underscores an urgent need for developing more sensitive and efficient detection technologies. In the field of bacterial and viral detection, polymerase chain reaction (PCR) technology has become a principal method for pathogen identification in both clinical and research settings, owing to its high sensitivity and specificity [109]. This technique enables the exponential amplification and precise identification of pathogen nucleic acids from trace amounts of sample within hours, providing critical molecular evidence for the early diagnosis and targeted intervention of infectious diseases. However, the broad application of PCR is constrained by its stringent operational requirements, which include reliance on standardized laboratory settings, high-precision instrumentation, and trained personnel. Due to its inherent dependence on fixed laboratory infrastructure and specialized expertise, the technology is intrinsically limited in its applicability and is poorly suited to meet the demands for on-site and rapid screening, such as those required for monitoring pathogens in environmental water samples [110]. Microscopic examination serves as the fundamental diagnostic method for parasitic diseases. The feasibility of this method is limited in underdeveloped, high-endemicity regions by a critical shortage of skilled microscopists [111]. These limiting factors led to alternating approaches, such as biosensing, which can overcome the drawbacks of the conventional diagnostic methods for viral infectious diseases.

Qiu et al. [112] developed a CRISPR/Cas12a-responsive dual-mode biosensing platform based on an aggregation-induced emission metal–organic framework nanozyme (AIE MOFzyme) and a DNA hydrogel for the highly sensitive and reliable detection of foodborne pathogens (Figure 4). In this study, an AIE MOFzyme with both aggregation-induced emission (AIE) properties and peroxidase-like activity was first constructed by encapsulating hemin into a 1,1,2,2-tetra(4-carboxylphenyl)ethylene (TCPE)-based zirconium MOF via an *in situ* encapsulation strategy. Subsequently, a smart hydrogel sensing platform was fabricated by embedding the AIE MOFzyme into a DNA hydrogel formed via rolling circle amplification (RCA). For detection, the target pathogen gene is amplified by recombinase polymerase amplification (RPA) and subsequently activates the trans-cleavage activity of CRISPR/Cas12a, which cleaves the single-stranded DNA (ssDNA) network of the DNA hydrogel, leading to hydrogel collapse and the release of AIE MOFzyme. This results in a significant dual-signal output via fluorescence and colorimetric readouts. Using Salmonella enterica as a model analyte, the sensor achieved a detection limit of 1 CFU/mL in fluorescence mode with a linear range of 101–108 CFU/mL, and a detection limit of 15.9 CFU/mL in colorimetric mode with a linear range of 102–108 CFU/mL. These results demonstrate that the sensor exhibits superior sensitivity compared to most existing detection methods. The AIE MOFzyme retained approximately 80% of its initial activity after 30 days of storage at 25 °C, demonstrating good storage stability. Furthermore, the fluorescence intensity of the AIE MOFzyme showed no significant change throughout the 30-day storage experiment. These results demonstrate that the AIE MOFzyme exhibits excellent long-term stability, highlighting its promising potential for biosensing applications.

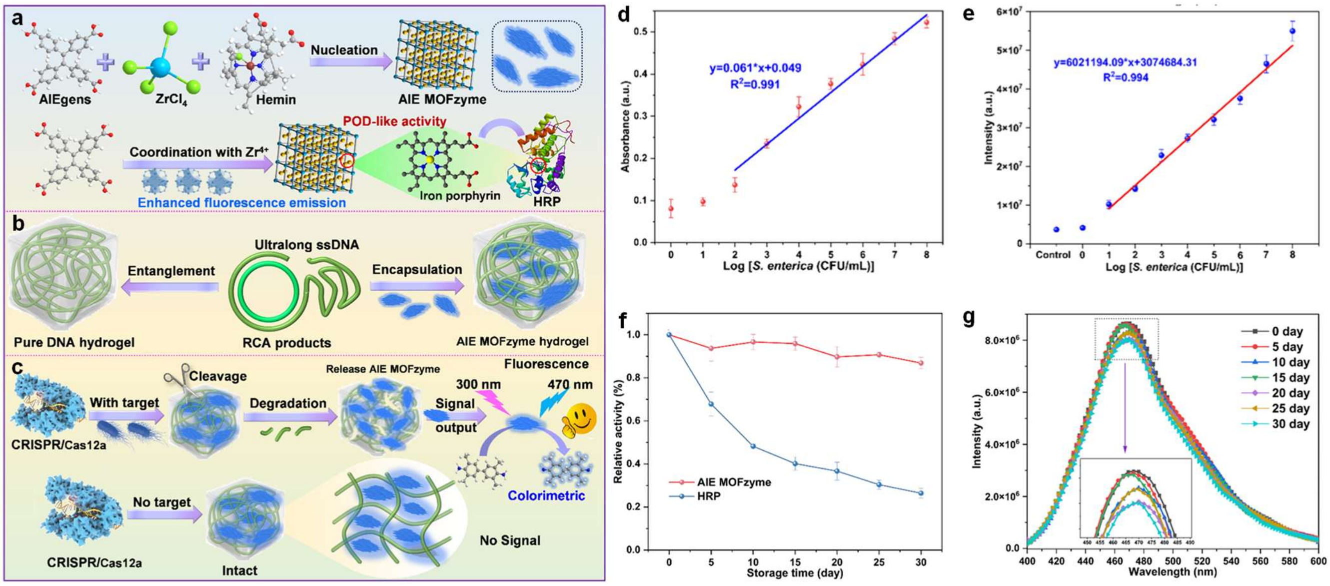

Figure 4. Schematic illustration of **(a)** AIE MOFzyme fabrication; **(b)** AIE MOFzyme hydrogel formation; and **(c)** the assembly and working principle of the Cas12a–H–AIE biosensor; **(d)** Linear range of the colorimetric signal mode of the Cas12a–H–AIE biosensing platform for detecting S. Enterica; **(e)** Linear range of the fluorescence signal mode of the Cas12a–H–AIE biosensing platform for detecting S. Enterica; **(f)** The effect of storage time on the catalytic activity; **(g)** the fluorescence property of AIE MOFzyme. (Reprinted and adapted with permission from [112], American Chemical Society, 2025).

3.2. Detection of Antibiotics Using MOF–Hydrogel Composites

Antibiotics comprise a class of organic compounds that exert inhibitory or lethal effects on a broad spectrum of pathogenic microorganisms, including bacteria, fungi, protozoa, and some parasites [113–115]. In 1929, penicillin was first discovered, marking the advent of the antibiotic era in human medicine. Since then, a wide array of antibiotics has been developed and deployed, fundamentally transforming the protection of human and animal health. The classification of established antibiotics rests primarily on differences in their chemical structures or mechanisms of action, encompassing classes like aminoglycosides, β-lactams, macrolides, tetracyclines, nitroimidazoles, streptogramins, quinolones, and lincosamides [116]. Owing to their production via natural, semi-synthetic, and fully synthetic routes, antibiotics exhibit a ubiquitous environmental occurrence. Although most antibiotics have relatively short half-lives, they are recognized as persistent environmental pollutants due to long-term application and continuous accumulation. Beyond posing direct risks to human health by disrupting metabolism and gut flora, antibiotics in the environment further drive the emergence and spread of antibiotic resistance, constituting a profound long-term threat to ecological and public health security. Chromatographic techniques such as high-performance liquid chromatography (HPLC) and liquid chromatography–mass spectrometry (LC–MS) have been established as reliable methods for antibiotic detection [117,118]. Despite their cap ability for trace-level detection, the utility of these chromatographic techniques remains confined by the necessity for advanced instrumentation, specialized technical skills, and labor-intensive sample processing. While the enzyme-linked immunosorbent assay (ELISA) remains a cornerstone technique for antibiotic detection, its operational efficiency is often limited by labor-intensive procedures and prolonged incubation periods [119]. Consequently, MOF–hydrogel composites have emerged as a promising platform, opening up new avenues for antibiotic detection.

Jiang et al. [120] developed a colorimetric aptasensor based on a metal–organic framework hybrid (MOFzyme) integrated with a nucleic acid hydrogel for the highly selective and sensitive detection of sarafloxacin (Sar) (**Figure 5a**). The sensor was constructed by encapsulating catalase within an MOF matrix to form a MOFzyme, which was then incorporated into a hyaluronic acid-DNA hydrogel functionalized with an evolved aptamer. In the presence of Sar, its binding to the aptamer triggers the disintegration of the hydrogel, releasing the MOFzyme to catalyze the oxidation of TMB by H_2O_2 and generate a colorimetric signal. The sensor achieved a low detection limit of 2.06 pg/mL with a wide linear range of 0.003–200 ng/mL. The MOF@cat@MOF composite demonstrates remarkable long-term stability. After 30 days of storage at room temperature, no significant decline in catalytic activity is observed, with 95.1% of its initial performance retained. Furthermore, following encapsulation within a DNA hydrogel matrix, the composite maintains consistent sensing responsiveness after two months under storage conditions of 4 °C and pH 7.0–8.0. This directly demonstrates the excellent long-term storage stability of the composite material.

Correspondingly, He et al. [121] reported an intelligent color-changing hydrogel platform for the dual-mode detection of kanamycin (KAN) (**Figure 5b**). This platform integrates coral-shaped Prussian blue nanozymes (C-PB) and gold polyhedra (AuNPH) into a hydrogel matrix, while employing an aptamer-DNA "lock" structure to regulate the encapsulation and release of TMB molecules from a MOF. Upon the introduction of KAN, TMB is released and absorbed into the hydrogel, where it is catalytically oxidized by C-PB. This oxidation process induces a visible color change of the hydrogel from pink to blue and simultaneously generates an enhanced Raman signal from the oxidized product under the influence of AuNPH, enabling dual-channel detection via both colorimetry and SERS. The method achieves a detection limit as low as 1.58×10^{-13} mol/L and a broad linear range from 1.0×10^{-12} to 1.0×10^{-3} mol/L, offering a highly sensitive and visually intuitive strategy for the real-time monitoring of antibiotics. Notably, Wang et al. [122] reported a novel SERS sensor based on a DNA hydrogel and a gold nanorod (AuNR) array for the ultrasensitive detection of streptomycin. The sensor consists of a DNA hydrogel loaded with DNAzyme and a Raman reporter molecule (4-mercaptobenzonitrile), combined with a vertically ordered AuNR array. The detection mechanism is as follows: streptomycin specifically binds to the aptamer, releasing Pb^{2+}, which subsequently activates the DNAzyme, leading to the cleavage of the DNA hydrogel and the release of the reporter molecule. The reporter molecules then adsorb onto the "hot spots" of the AuNR array, generating significantly enhanced SERS signals and enabling "signal-on" detection. This method achieves a detection limit as low as 4.85×10^{-3} nM with a linear range of 0.01–150 nM, exhibits high selectivity for streptomycin, and provides an effective tool for the sensitive and rapid detection of antibiotic residues.

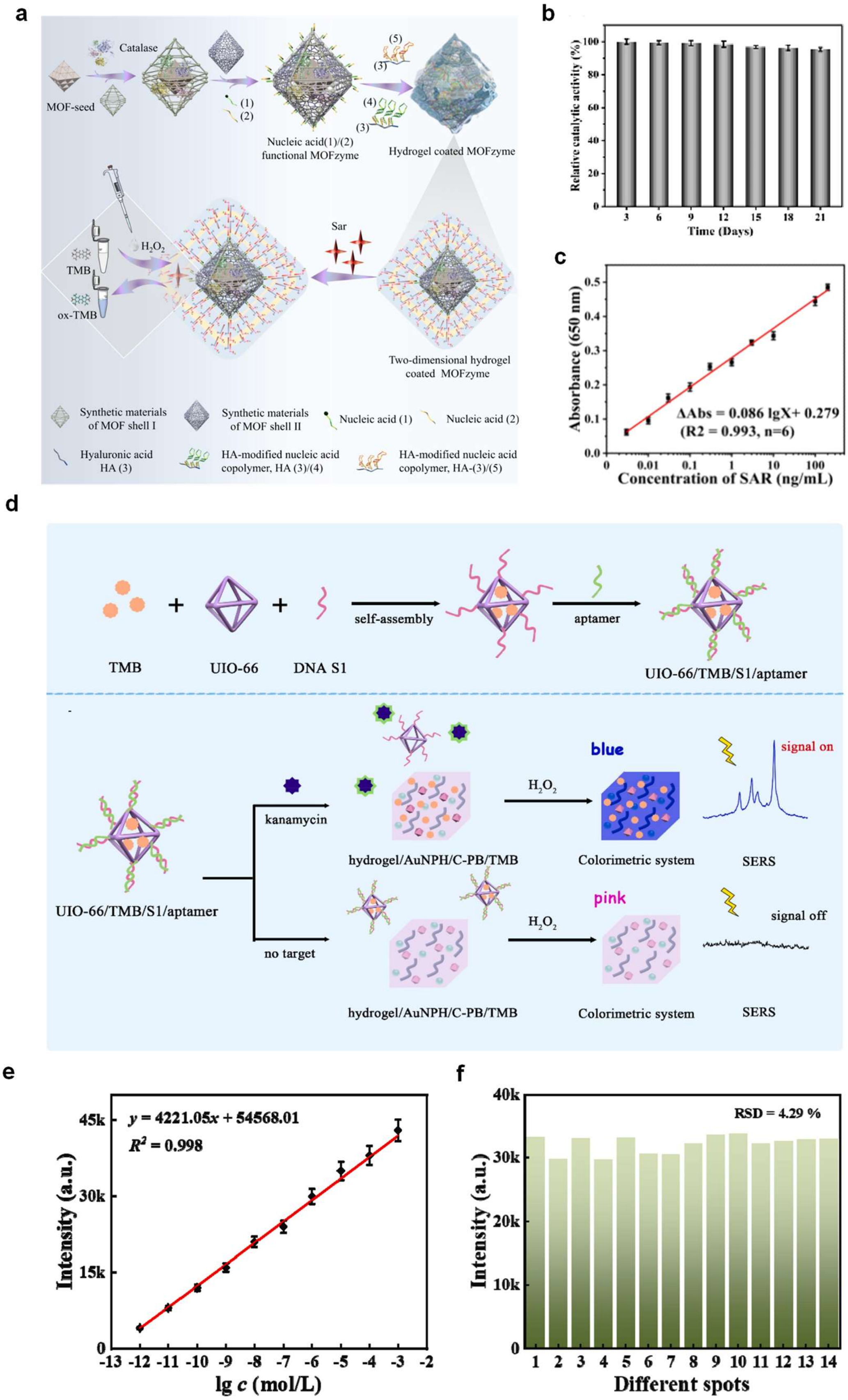

Figure 5. Schematics of MOF–hydrogel optical biosensing platforms for antibiotic detection. **(a)** Schematic illustration of the Sar detection mechanism using an aptasensor based on a hyaluronic acid-DNA hydrogel-coated MOFzyme; **(b)** Long-term storage stability of MOFzyme; **(c)** Linear curve between the changed absorbance and the Sar concentration

on logarithmic scales within the range of 0.003–200 ng/mL. (Reprinted and adapted with permission from [120], American Chemical Society, 2025); **(d)** Schematic illustration of the working principle for an intelligent hydrogel–based kanamycin detection platform; **(e)** Linear equation of CAP concentration and SERS intensity at 1615 cm^{-1}; **(f)** Raman spectra were obtained by repeating the experiment five times under the same conditions (Reprinted and adapted with permission from [121], Elsevier Science, 2025).

3.3. Detection of Heavy Metal Ions Using MOF–Hydrogel Composites

Industrialization and technological development have driven the expanding applications of heavy metal ions, resulting in their continuous release into the environment from various anthropogenic sources. However, their excessive discharge and accumulation lead to severe ecosystem toxicity and directly jeopardize the health of humans, animals, and plants. Among these, mercury (Hg^{2+}), cobalt (Co^{2+}), copper (Cu^{2+}), and nickel (Ni^{2+}) are predominantly found as divalent cations in the environment, and their excessive exposure is associated with a range of adverse health effects. In response to the environmental and health impacts of heavy metal pollution, researchers have focused on advancing precise and reliable techniques for contaminant detection and quantification. Conventional approaches for heavy metal analysis primarily encompass spectroscopic techniques such as atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (IPC-MS) and inductively coupled plasma atomic emission spectrometry (IPC-AES) [123–125]. Despite their high sensitivity and selectivity, the application of these techniques is often restricted by demanding requirements for specialized instrumentation, skilled personnel, and laborious sample pretreatment including preconcentration steps. Moreover, they cannot be used as portable devices for on-site detection. In contrast, biosensing has great potential in high throughput detection of multiple heavy metal ions on-site [126]. This section focuses on the application of biosensing platforms based on MOF–hydrogel composites for the detection of heavy metal ions in the environment.

Mao et al. [127] developed a europium metal-organic framework (Eu–MOF)-integrated hydrogel bioreactor for the sensitive and portable detection of Hg^{2+} (**Figure 6**). In this study, a rod-like Eu–MOF with strong fluorescence was first synthesized. It has been demonstrated that ssDNA can quench the fluorescence of Eu–MOF through electrostatic interactions and π–π stacking. In the presence of Hg^{2+}, ssDNA undergoes a conformational transition to form a T–Hg–T structure, which induces the dissociation of ssDNA from Eu–MOF and subsequent fluorescence recovery. Based on this “quenching–recovery” fluorescence mechanism, Eu–MOF and programmable ssDNA were co-embedded in an agarose hydrogel to construct a quasi-liquid bioreactor. This bioreactor integrates the solid-like stability of hydrogels with the liquid-like diffusivity of reactants, thereby laying a foundation for the sensitive and portable detection of Hg^{2+}. During detection, Hg^{2+} diffuses into the hydrogel, triggering DNA conformational switching and fluorescence recovery; the fluorescence signal can be quantified by analyzing the red channel (R) value of fluorescence images captured via a smartphone. This sensor exhibits a linear detection range of 5 nM to 10 μM for Hg^{2+}, with a limit of detection as low as 1.42 nM. The MOF–hydrogel composite ensures the dispersion stability of Eu–MOF and confers enhanced resistance to matrix interference. The hydrogel network effectively inhibits the aggregation and sedimentation of Eu–MOF particles, while maintaining a fluorescence recovery of 83.14% even in nuclease-containing complex matrices. Following 9 days of room-temperature storage, the composite retains its structural integrity and a uniform dispersion of Eu–MOF.

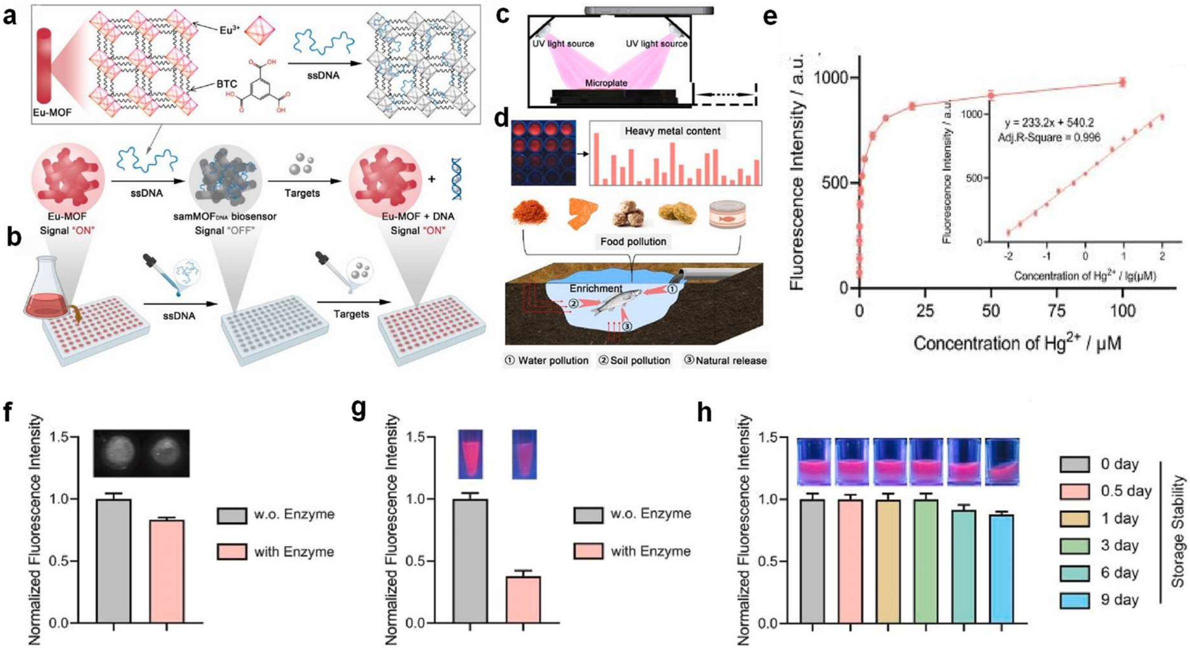

Figure 6. Schematic illustration of MOF integrated bioreactor. **(a)** Schematic illustration of the target detection based on MOF integrated bioreactor; **(b)** Schematic illustration of the target detection based on MOF integrated hydrogel bioreactor; **(c)** Schematic illustration of the smartphone-based imaging platform; **(d)** Schematic illustration of heavy metal ions detection based on MOF integrated hydrogel bioreactor; **(e)** linear function of Hg^{2+} detection based on MOFpolyT integrated bioreactor. The anti-enzymatic interference ability of **(f)** MOFDNA integrated hydrogel bioreactor and **(g)** MOFDNA integrated bioreactor; **(h)** The storage stability of MOFDNA integrated hydrogel bioreactor. (Reprinted and adapted with permission from [127], Elsevier Science, 2024).

3.4. Detection of Pesticides Using MOF–Hydrogel Composites

Pesticides have emerged as an increasingly critical contributor to boosting agricultural productivity [128–130]. However, their extensive and improper use has inevitably resulted in adverse impacts of pesticide residues on human health, animal welfare, as well as aquatic and soil ecosystems [131–133]. Chronic exposure to pesticide residues can elicit damage to the nervous and immune systems, thereby increasing susceptibility to a range of associated diseases. To regulate pesticide residues and mitigate their hazards, numerous countries have established Maximum Residue Limits (MRLs). Consequently, the development of time-efficient, high-throughput, sensitive, and accurate detection technologies for pesticide residues is of paramount importance for environmental monitoring [134]. Over recent years, a range of methodologies for pesticide residue detection have been established, spanning from conventional analytical techniques to novel biosensor-based approaches. Conventional methods, including HPLC, mass spectrometry (MS), gas chromatography (GC) and their combined applications, are recognized as gold-standard methods for pesticide residue detection due to their established effectiveness and high accuracy [135–137]. However, those methods for the detection of pesticide residues are always limited because they are very complex, time and labor consuming, need tedious sample pretreatment and expensive equipment, and also need professional workers [138]. Additionally, while the ELISA has been utilized for pesticide residue detection, it is generally not amenable to on-site testing. On this ground, new biosensing platforms, including optical and electrochemical methods, have been developed for pesticide residue detection. These approaches offer enhanced operational simplicity and analytical sophistication compared to traditional techniques, enabling rapid, specific, and highly sensitive field testing. This section focuses on the application of biosensing platforms based on MOF–hydrogel composites for the detection of pesticide residues in the environment.

Lu et al. [139] developed a platinum-metal organic framework (MOF–Pt) - enhanced long-lasting chemiluminescence hydrogel sensing platform for the highly sensitive and high-throughput detection of organophosphorus pesticides (OPs) and D-amino acids (D-AAs) (**Figure 7a**). In this work, a sensing platform with enhanced chemiluminescence performance was constructed by incorporating MOF–Pt into the ABEI/Co^{2+}/CS hydrogel system. The detection mechanism relies on the enzymatically generated H_2O_2 as the signal transducer. For OPs, they inhibit the activity of acetylcholinesterase (AChE), which reduces H_2O_2 generation and thus leads to a diminished luminescence signal. In contrast, D-AAs are enzymatically oxidized by D-amino acid oxidase (DAAO) to produce H_2O_2, thereby enhancing the luminescence signal. MOF–Pt exerts a synergistic catalytic effect with Co^{2+}, enhancing the luminescence intensity by approximately 6-fold. This sensor achieves a limit of detection of 0.21 ng/mL for chlorpyrifos, with a linear range spanning from 0.5 ng/mL to 1.0 μg/mL; for D-alanine, it exhibits a limit of detection of 0.12 μM, paired with a linear range of 1.0 μM to 10 mM, thus demonstrating high sensitivity and favorable practicality in array detection. Li et al. [140] reported a portable hydrogel test kit based on a dual-emission coordination polymer nanocomposite for the on-site detection of organophosphorus pesticides (**Figure 7b**). This kit integrates a ruthenium complex and zinc-based coordination polymers loaded with thioflavin T into an agarose hydrogel. The detection principle relies on the inhibition of acetylcholinesterase activity by pesticides, which prevents the hydrolysis of the substrate and the subsequent generation of acid. The acidic environment disrupts the structure of the zinc-based coordination polymers and quenches their green fluorescence, whereas the red fluorescence of the ruthenium complex remains stable and serves as an internal reference, thus enabling a ratiometric fluorescence response. This method achieves a limit of detection of 0.05 ng/mL, with a linear range spanning from 1 to 600 ng/mL. Following 30-day storage in aqueous solution at room temperature, ThT@ZnCPs shows no evident alteration in its morphology or fluorescence properties, confirming the robust chemical and structural stability of this zinc-based coordination polymer. The resulting composite, formed by integrating ThT@ZnCPs with agarose hydrogel, exhibits a stable fluorescence signal output with the G/R ratio remaining nearly unchanged after 14 days of storage under ambient conditions. This observation indicates that the hydrogel matrix effectively protects and stabilizes the functional performance of the embedded material. In summary, the hydrogel composite system effectively maintains the intrinsic stability of MOF–based materials while also improving their overall robustness during extended storage and real-world detection.

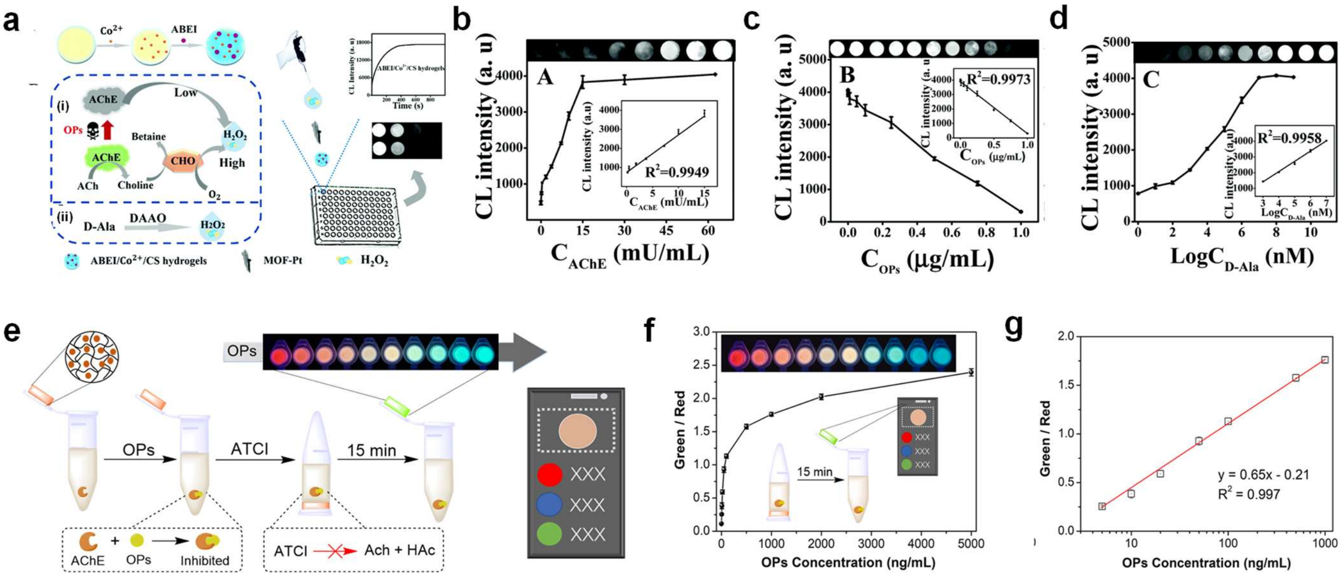

Figure 7. Schematic of the detection mechanisms for pesticides using MOF–hydrogel optical platforms. **(a)** Schematic diagram of the detection of OPs and D-AAs based on MOF–Pt enhanced long-lasting CL of ABEI/Co^{2+}/CS hydrogels; **(b)** CL intensity changed with AChE at various concentrations (0, 0.2, 0.45, 0.9, 1.8, 3.75, 7.25, 15, 30, and 62.5 mU/mL); **(c)** CL intensity changed with chlorpyrifos at various concentrations (0.05, 0.1, 0.5, 1.0, 10, 50, 100, 250, 500, 750, and 1000 ng/mL); **(d)** CL intensity changed with D-Ala at various concentrations (0, 1.0 nM, 10 nM, 0.1 μM, 1.0 μM, 10 μM, 0.1 mM, 1.0 mM, 10 mM, and 0.1 M). (Reprinted and adapted with permission from [139], Royal Society of Chemistry,2020); **(e)** Schematic illustration of the working principle of the hydrogel test kit for on-site detection of Ops; **(f)** Ratios of green/red value and fluorescence images (inset) of the hydrogel test kit in the presence of OPs with different concentrations; **(g)** Linear calibration plots of the ratio of green/red value against OPs concentration. (Reprinted and adapted with permission from [140], Elsevier Science, 2023).

3.5. Application of MOF–Hydrogel Composites in Real Environments

Compared to laboratory-prepared simulated solutions, real aqueous environments typically contain natural organic matter, complex ionic matrices, suspended particulates, and microbial communities. These components can significantly interfere with the intended functionality of materials through mechanisms such as competitive adsorption, active-site masking, or induced structural dissociation. Therefore, evaluating the long-term stability, anti-interference capability, and practical performance of MOF–hydrogel composite-based biosensing methods in real aqueous environments represents a critical step in bridging laboratory research and engineering applications. It also provides direct guidance for optimizing composite design tailored to specific environmental scenarios. This section systematically summarizes the detection limits of this method for environmental pollutants and its application in real water systems (**Table 2**).

Table 2. Key analytical performance metrics for the target analytes.

Analyte	LOD[a]	LOQ[b]	WHO[c]	Sample	Recovery (%)	RSD[d] (%)	Storage Time[f] (Days/ Temperature)	Reference
Salmonella enterica	1 CFU/mL	10^1–10^8 CFU/mL	(No inspection)/25g	Milk	102–117	<7.26	/[e]	[112]
				Eggs	88–92	<8.59		
				Meat	101–112	<9.30		
Sarafloxacin	0.0021 ng/mL	0.003–200 ng/mL	10 ng/mL	Lake water	95–99	<1.50	60/4°C	[120]
				Milk	91–98	<2.40		
				Beef	90–98	<3.50		
Kanamycin	7.65×10^{-5} ng/mL	0.48–484.4 ng/mL	50 ng/mL	Milk	97–103	<9.7	/[e]	[121]
				Honey	95–101	<8.5		
Streptomycin	2.82×10^{-3}ng/mL	5.82×10^{-3}–87.2 ng/mL	200 ng/mL	Honey	99–117	<2.55	/[e]	[122]
				Milk	98–117	<3.6		
Hg^{2+}	0.285 ng/mL	1–2010 ng/mL	0.05 ng/mL	Freshwater fish	100–107	/[e]	9/Room temperature	[127]
OPs	0.21 ng/mL	0.5–1000 ng/mL	≤ 10 ng/mL	Pakchoi	93–110	<5.32	/[e]	[139]
D-AAs	11 ng/mL	89.1–8.9×10^5 ng/mL	/[e]	Serum	97–109	<6.20		
OPs	1.8 ng/mL	5–1000 ng/mL	≤ 10 ng/mL	Apple juice	97–107	<1.80	14/Room temperature	[140]

[a] Limit of detection; [b] Limit of quantitation; [c] The WHO-defined maximum permissible level of this contaminant in food or drinking water; [d] Relative standard deviation towards the recovery; [e] Not mentioned. [f] The storage period of MOF–hydrogel composite materials.

4. Conclusions and Future Perspectives

In summary, this review outlines the engineering strategies of MOF–hydrogel composites and the representative applications of these composites as optical biosensing platforms in environmental pollutants detection. By synergistically combining the high porosity, tunable functionality, and catalytic properties of MOFs with the biocompatibility, stimuli-responsiveness, and mechanical adaptability of hydrogels, these composites offer enhanced sensitivity, selectivity, and operational versatility over their individual components. Their application in optical biosensing presents a powerful and often label-free approach for monitoring trace-level contaminants in complex environmental matrices.

Looking forward, several key research directions promise to propel this field toward broader practical implementation:

(1) Enhancing Environmental Stability: Future efforts should focus on improving the long-term chemical and mechanical robustness of MOF–hydrogel composites under real-world conditions (e.g., variable pH, temperature, ionic strength, and microbial activity). Strategies may include the development of more stable MOF

structures, protective hydrogel matrices, or novel crosslinking chemistries to ensure reliable sensor performance over extended deployment periods.

(2) Enabling Multi-Target Detection: The complexity of environmental samples necessitates sensors capable of simultaneous detection of multiple analytes. Advancing design strategies to integrate multiple recognition elements (e.g., different MOFs or functional groups) within a single composite device, coupled with multiplexed optical readout systems, will be crucial for comprehensive environmental monitoring.

(3) Advancing System Portability and Intelligence: The transition from laboratory prototypes to field-deployable tools requires a concerted push toward miniaturization, portability, and system integration. Combining MOF–hydrogel sensors with portable optical components (e.g., smartphone-based detectors, handheld spectrometers) and integrating them with wireless data transmission and machine learning algorithms for data analysis will facilitate real-time, on-site monitoring and intelligent decision-making.

(4) Expanding Application Horizons: While promising for aqueous sensing, the application scope should be expanded to include monitoring of pollutants in soils, sediments, and atmospheric interfaces. Furthermore, exploring their utility in more challenging scenarios, such as in extreme environments or for in-situ monitoring within industrial processes, will demonstrate the full versatility of these materials.

(5) Promoting Sustainability through Recycling: To align with green chemistry principles, developing efficient methods for the recovery and re-use of metal ions (or linker molecules) from spent MOF–hydrogel composites is an important sustainability challenge. Research into low-energy recycling protocols, including chemical etching, electrochemical recovery, or hydrogel-assisted leaching, will contribute to the life-cycle management and reduce the environmental footprint of these sensor materials.

Addressing these challenges will not only solidify the foundation of MOF–hydrogel-based optical biosensing but also accelerate its adoption as a reliable, efficient, and sustainable technology for safeguarding environmental health.

Funding: This project is supported by National Natural Science Foundation (22406140), and special fund of State Key Laboratory of Regional Environment and Sustainability (24K15ESPCT).

Conflict of interest: The authors declare no conflict of interest.

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