

Review

Recent Advances in MOF-Based Nanozymes for Intelligent Microbial Biosensing: A Comprehensive Review of Biomedical and Environmental Applications

Alemayehu Kidanemariam¹ and Sungbo Cho^{1,2,3*}

¹Department of Electronic Engineering, Gachon University, Seongnam-si, Gyeonggi-do 13120, Republic of Korea.

²Department of Semiconductor Engineering, Gachon University, Seongnam-si, Gyeonggi-do 13120, Republic of Korea.

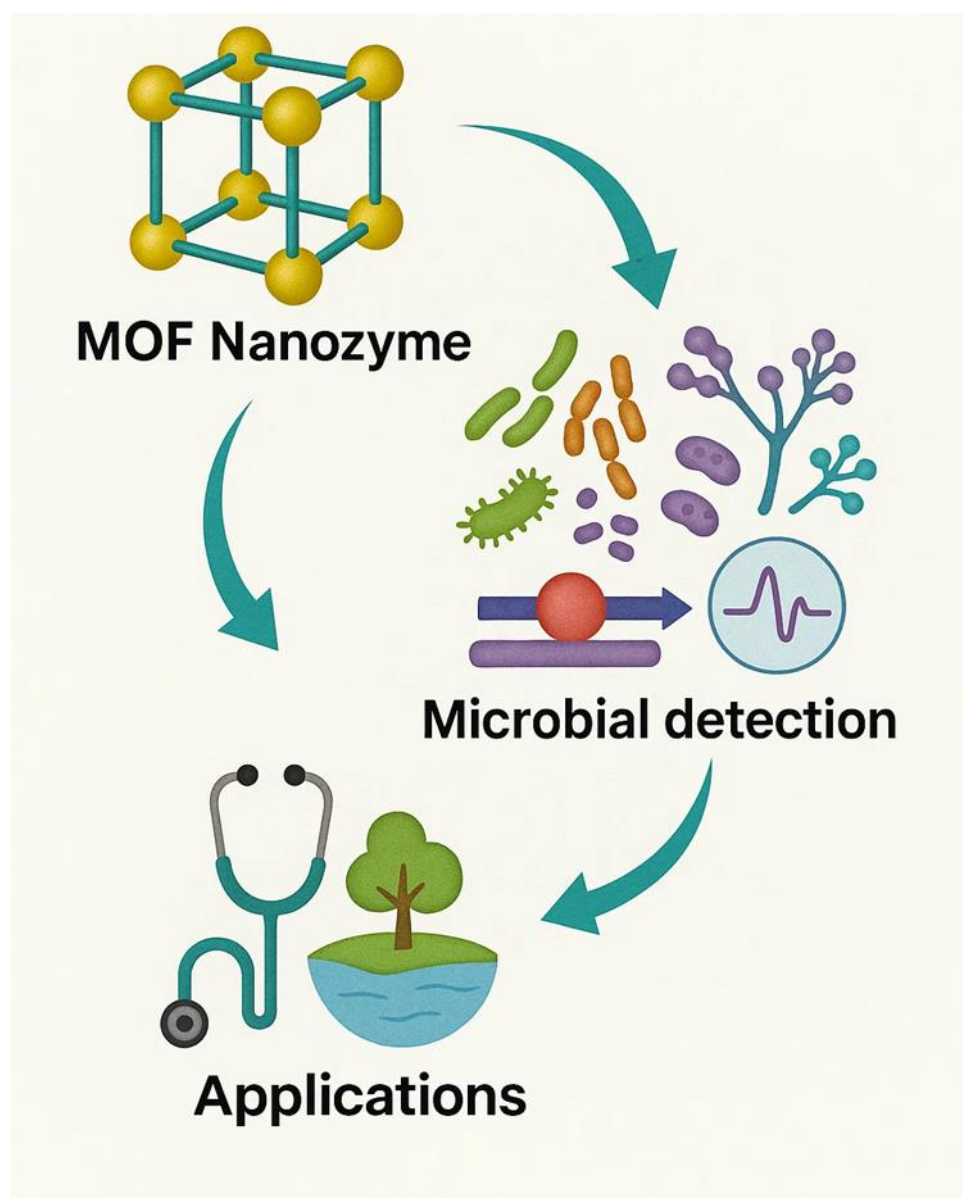
³Gachon Advanced Institute for Health Science & Technology, Gachon University, Incheon 21999, Republic of Korea.

*Correspondence: sbcho@gachon.ac.kr

Abstract: Metal-organic framework (MOF)-based nanozymes represent a groundbreaking frontier in advanced microbial biosensing, offering unparalleled catalytic precision and structural tunability to mimic natural enzymes with superior stability and specificity. By engineering the structural features and forming composites, MOFs are precisely tailored to amplify nanozymatic activity, enabling highly sensitive, rapid, and cost-effective detection of a broad spectrum of microbial pathogens critical to biomedical diagnostics and environmental monitoring. These advanced biosensors surpass traditional enzyme systems in robustness and reusability, integrating seamlessly with smart diagnostic platforms for real-time, on-site microbial identification. This review highlights cutting-edge developments in MOF nanozyme design, composite engineering, and signal transduction integration, while addressing pivotal challenges such as biocompatibility, complex matrix interference, and scalable manufacturing. Looking ahead, the convergence of multifunctional MOF nanozymes with portable technologies and optimized in vivo performance will drive transformative breakthroughs in early disease detection, antimicrobial resistance surveillance, and environmental pathogen control, establishing a new paradigm in next-generation smart biosensing.

Keywords: MOF-based nanozymes, Microbial biosensing, Point-of-care diagnostics, Enzyme mimetics, Biomedical and Environmental Applications.

Graphical Abstract



1. Introduction

The global burden of infectious diseases, the rise of antimicrobial resistance, and increasing environmental contamination have underscored the urgent need for rapid, sensitive, and reliable microbial detection technologies [1–3]. Early identification of pathogenic microorganisms is essential for effective outbreak response, informed treatment decisions, and public health management in settings ranging from hospitals and food production to water quality monitoring [4,5].

Traditional microbial detection methods including culture-based assays, polymerase chain reaction (PCR), and enzyme-linked immunosorbent assays (ELISA) have long served as diagnostic gold standards [6–8]. However, these approaches are often time-intensive, laborious, and dependent on sophisticated instrumentation and trained personnel [9]. These constraints limit their applicability in decentralized and resource-limited environments where rapid decision-making is critical [10,11].

To overcome these limitations, significant research efforts have been directed toward the development of advanced biosensors using functional nanomaterials [12,13]. Nanomaterials such as noble metal nanoparticles (e.g., Au, Ag), carbon-based nanostructures (e.g., graphene oxide, carbon nanotubes), quantum dots, and magnetic nanoparticles have been explored for their unique physicochemical properties, enabling diverse detection modalities such as fluorescence, surface-enhanced Raman scattering (SERS), and electrochemical sensing [14–16]. These systems provide high sensitivity and rapid response but often face practical challenges, including poor stability under physiological conditions, limited biorecognition specificity, and potential cytotoxicity [17,18].

Enzyme-based biosensors offer high catalytic efficiency and specificity but suffer from inherent limitations such as environmental instability, high cost, and short shelf life due to protein denaturation [19–21]. These drawbacks have driven the emergence of nanozymes nanomaterials that mimic natural enzymatic activity while offering enhanced robustness and functional versatility [22,23]. Among various nanozyme candidates, metal–organic frameworks (MOFs) have garnered increasing attention for microbial biosensing due to their highly tunable structures and multifunctionality [24,25].

MOFs are crystalline, porous materials composed of metal nodes coordinated to organic linkers, forming extended three-dimensional architectures [26]. Their ultrahigh surface area, tunable pore environment, and modular chemistry make MOFs ideal platforms for mimicking enzymatic active sites and incorporating biorecognition elements [27,28]. Unlike conventional nanomaterials, MOFs offer the

advantage of structural programmability at the molecular level, allowing for precise control over catalytic behavior, target specificity, and sensor performance [29].

In the context of microbial detection, MOFs can serve dual roles: as nanozyme catalysts facilitating signal generation and as scaffolds for immobilizing recognition units such as aptamers, antibodies, DNA probes, and molecularly imprinted polymers [30,31]. These attributes have enabled the creation of highly sensitive and selective biosensors capable of detecting a wide range of microbial targets including bacteria (e.g., *E. coli*, *Salmonella*, *Staphylococcus aureus*) and viruses (e.g., influenza, SARS-CoV-2) through various transduction mechanisms such as colorimetric, fluorescent, electrochemical, and luminescent readouts [32–34].

Furthermore, the adaptability of MOFs has supported their integration into portable and digital diagnostic platforms [35]. The combination of MOF-based nanozymes with smartphone interfaces, paper-based sensors, and microfluidic systems is paving the way for next-generation point-of-care (POC) diagnostic tools [36]. These compact and affordable systems hold promise for on-site microbial monitoring in clinical, agricultural, and environmental applications, enabling real-time decision-making and outbreak containment [25,37].

This review aims to provide a comprehensive overview of the recent progress in MOF-based nanozymes for microbial detection and assay development. We examine key aspects of MOF nanozyme design, including catalytic mechanism tuning, surface modification strategies, and hybrid material construction. Emphasis is placed on the integration of MOFs with biorecognition molecules to enhance detection specificity and performance.

In addition, we critically analyze the current challenges associated with MOF nanozyme-based biosensors, such as matrix interference in complex samples, reproducibility issues, biocompatibility, and long-term stability. Potential strategies to address these challenges such as advanced composite engineering, robust synthesis protocols, and biointerface optimization are discussed. Finally, we explore future directions for the field, including the incorporation of MOFs into Internet of Things (IoT)-enabled smart diagnostic networks and regulatory considerations for their clinical translation.

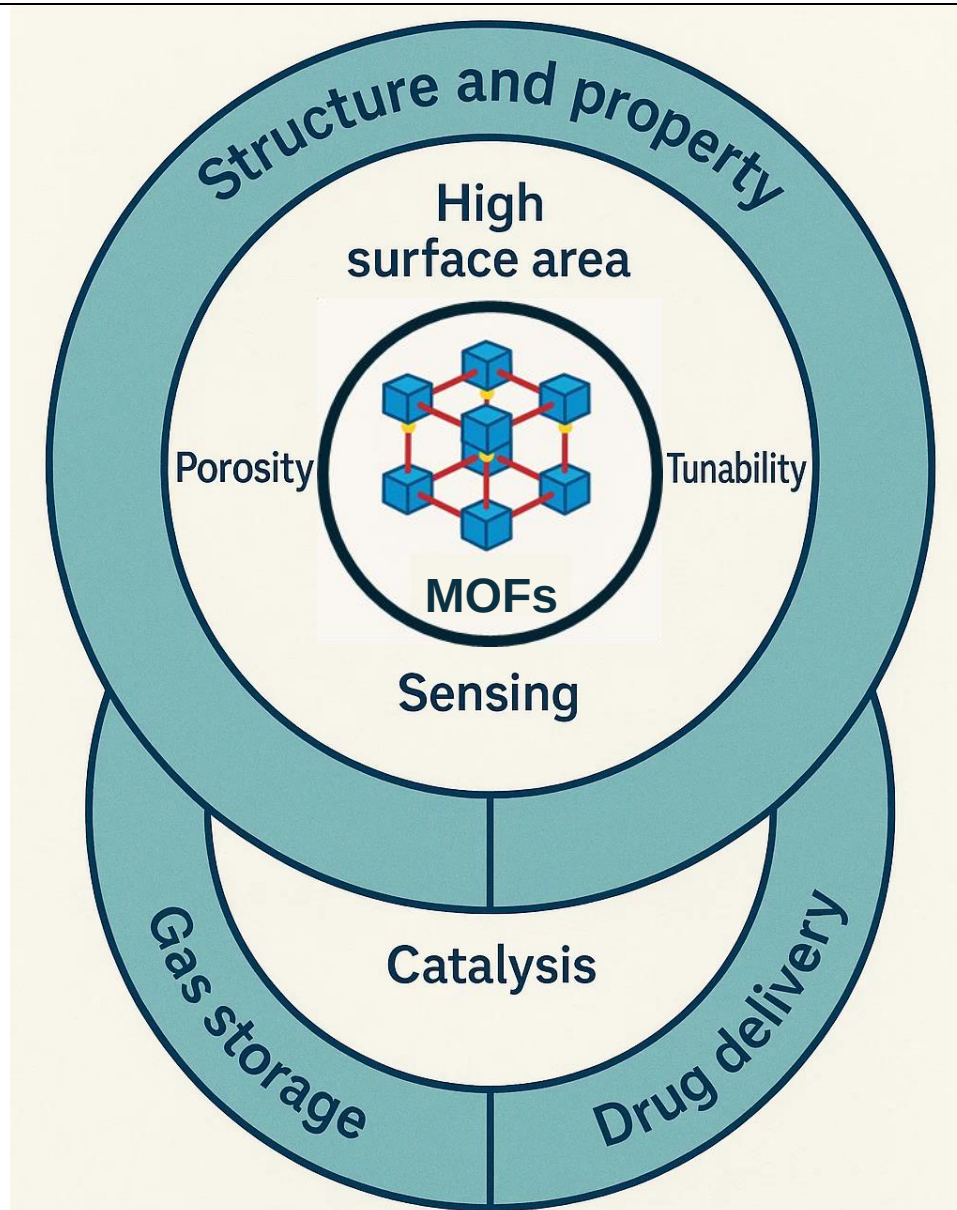
By synthesizing insights from materials science, microbiology, and sensor engineering, this review offers a strategic roadmap for harnessing MOF nanozymes in the development of next-generation biosensing technologies for microbial detection.

2. Fundamentals of MOF Nanozymes

The integration of metal–organic frameworks (MOFs) with nanozyme technologies has opened exciting avenues for the development of next-generation biosensors [38]. MOF nanozymes synergistically combine the advantages of MOFs such as high porosity, structural tunability, and chemical functionality with the catalytic properties of nanozymes that mimic natural enzymes [39].

2.1. Metal–Organic Frameworks: Structure and Properties

MOFs are crystalline porous materials composed of metal ions or clusters coordinated to organic ligands, forming highly ordered network structures [40]. Their defining characteristics include ultrahigh surface area, tunable pore sizes, and the ability to be chemically tailored at both the metal center and linker level [41]. This structural tunability allows for precise modulation of surface chemistry and functionality, enabling MOFs to be customized for a wide range of application areas such as catalysis, gas storage, drug delivery, and biosensing (**Scheme 1**) [42–44]. In the context of biosensing, their porosity and chemical versatility enable the selective adsorption and interaction with target microbial analytes, laying the structural foundation for nanozyme integration.



Scheme 1. Schematic overview of MOF properties and their application areas.

2.2. Nanozymes: Definition and Classification

Nanozymes are nanomaterials that exhibit intrinsic enzyme-like activities, mimicking natural enzymes such as peroxidase, oxidase, catalase, and superoxide dismutase [45,46]. Unlike their biological counterparts, nanozymes offer superior operational stability, ease of large-scale production, and enhanced resistance to harsh conditions [47]. They are broadly categorized based on their catalytic mechanisms, activities, and material composition. Owing to these properties, nanozymes have found significant utility in biosensing, where they amplify catalytic signals and improve the sensitivity and reliability of detection systems [48–50].

A representative example is the porphyrin-based porous polymer, FePPOP-1, reported by Cui et al., synthesized via Sonogashira–Hagihara

coupling [51]. FePPOP-1 exhibits a high surface area, strong stability, and peroxidase-like activity, catalyzing the oxidation of 3,3',5,5'-tetramethylbenzidine (TMB) in the presence of hydrogen peroxide (H_2O_2). A colorimetric biosensor based on FePPOP-1 was developed for the sensitive detection of H_2O_2 , glucose, and antioxidants such as ascorbic acid, gallic acid, and tannic acid. The varied inhibitory responses suggest distinct antioxidative mechanisms.

In another application, Smutok et al. developed a selective and sensitive biosensor for L-lactate detection an important metabolite in food and beverage processing [52]. This system integrated peroxidase-mimetic nanozymes with microbial lactate oxidase (LOx) immobilized on a graphite-rod electrode. The nanozymes were synthesized from carbon microfibers functionalized with hemin and modified with either gold nanoparticles or platinum microparticles. The platinum-based variant (LOx-CF-H-PtMPs/GE) exhibited superior catalytic performance and was successfully applied to quantify L-lactate in grape must and red wine, showing high correlation with conventional spectrophotometric methods. This approach demonstrates potential not only in food technology but also in clinical diagnostics where precise L-lactate analysis is crucial.

Moreover, oxidative stress is a key pathological factor in dry eye disease (DED), a prevalent ocular disorder with limited effective treatments. Addressing this, Zou et al. designed cerium oxide nanozymes modified with branched poly(ethylene imine)-graft-poly(ethylene glycol) (CNP@bPEI-g-PEG), enhancing water solubility, biocompatibility, and antioxidant performance [53]. These nanozymes mimic superoxide dismutase and catalase activities and are capable of regenerative ROS scavenging through cerium redox cycling (**Figure 1**). In vivo experiments confirmed their therapeutic efficacy, showing reduced oxidative damage, restoration of corneal and conjunctival integrity, and increased goblet cell density. This strategy holds promise for effective DED therapy via oxidative stress modulation.

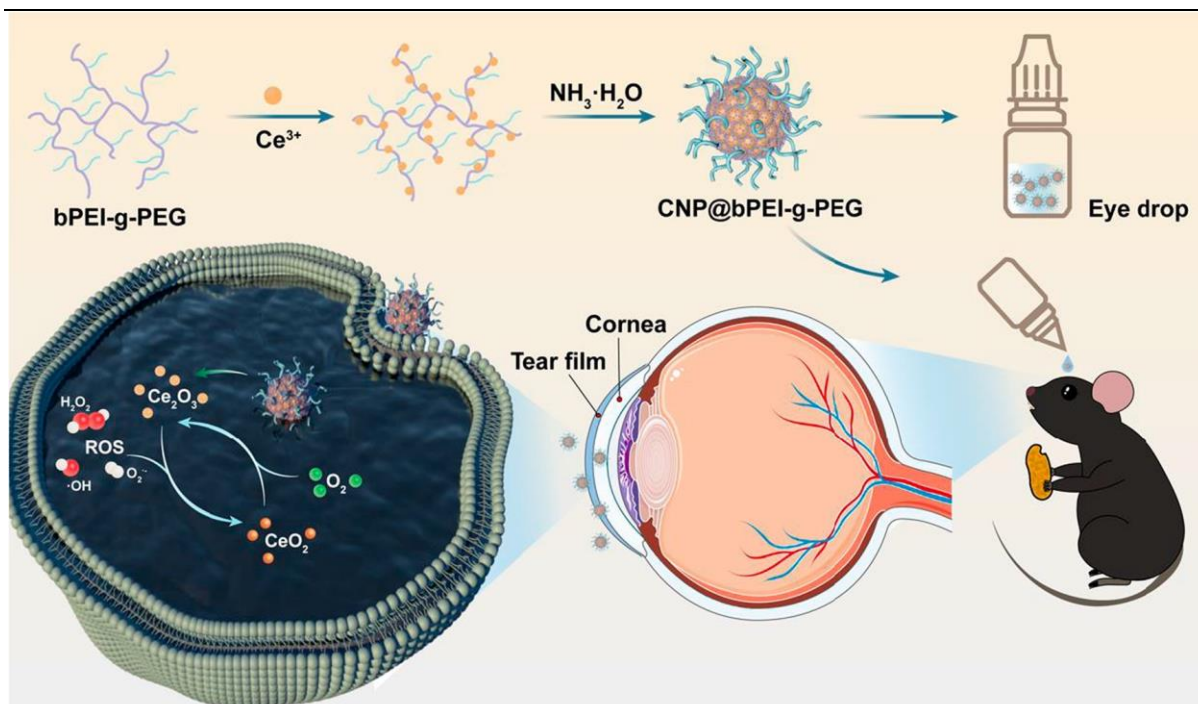


Figure 1. Schematic illustration of the CNP@bPEI-g-PEG nanozymes and antioxidative damage mechanism for DED. Copyright 2022 Regenerative Biomaterials [53].

Similarly, Ali et al. reported a multi-enzyme mimetic composite, $\text{Mn}_3\text{O}_4@\text{g-C}_3\text{N}_4$, synthesized via a solid-state mixing method [54]. The integration of mixed-valence Mn_3O_4 onto layered $\text{g-C}_3\text{N}_4$ endowed the composite with diverse enzyme-like activities, including those of including superoxide dismutase (SOD), catalase (CAT), oxidase (OD), and peroxidase (POD). This multifunctional nanozyme effectively scavenged reactive oxygen species (ROS), particularly superoxide radicals from cigarette smoke. Furthermore, it functioned as a label-free colorimetric probe for the selective detection of phenolic pollutants, hydroquinone and catechol, with visual discrimination capability and excellent sensitivity.

Collectively, these studies highlight the versatility and impact of nanozymes in biomedical, environmental, and industrial applications. Their tunable properties and multifunctional behavior position them as next-generation catalytic tools for addressing challenges in diagnostics, therapeutics, and sustainable chemical processes.

2.3. MOFs as Nanozyme Platforms

MOFs provide a unique and versatile scaffold for constructing nanozymes, owing to their ability to spatially isolate catalytic sites, host metal centers with redox activity, and allow for the diffusion of substrates through their porous matrices [55]. The confinement effect and high local concentration of active sites within MOFs often lead to enhanced catalytic

efficiency compared to other nanozyme platforms [56]. Moreover, the modularity of MOF design enables the rational incorporation of functional groups and metal species tailored to specific microbial sensing mechanisms [57]. As such, MOFs serve not only as passive supports but also as active participants in enzyme-mimetic catalysis, offering vast potential in intelligent biosensing applications [58].

3. Design Strategies for MOF Nanozymes in Microbial Biosensing

The performance of MOF nanozymes in microbial biosensing applications is strongly influenced by how their structural and functional properties are engineered [59]. Strategic modifications at the metal center, organic linker, particle size, and hybrid composition levels enable precise control over catalytic activity, selectivity, and interaction with microbial targets [44,60].

3.1. Metal Center Engineering

The metal nodes within a MOF framework play a pivotal role in defining the catalytic behavior of nanozymes [61]. By selecting metals such as Fe, Co, Cu, or Mn with known redox activity, researchers can tailor the enzyme-mimicking functions such as peroxidase-like or oxidase-like behavior of MOFs [62]. This tunability allows for optimization of reaction kinetics, redox potential, and substrate specificity, which are essential for achieving high sensitivity and rapid response in microbial detection [63].

For instance, Ren et al. develop a mechanism for metal center engineering of a cobalt-based metal–organic framework (MOF) was employed to enhance its oxidase-like catalytic activity [60]. Specifically, structural defects were intentionally introduced into a zeolitic imidazolate framework (ZIF-L-Co) by doping with cysteine (Cys), a sulfur-containing ligand (**Figure 2**). This doping process disrupted the coordination environment between cobalt and nitrogen, leading to lattice distortion and increased oxygen adsorption capacity. As a result, the nanozyme exhibited significantly enhanced multi-oxidase mimic activities, including ascorbate oxidase-, glutathione oxidase-, and laccase-like functions, with activity increases of over 5-fold, 2-fold, and 3-fold, respectively. The optimized ZIF-L-Co nanozyme (10 mg) was incorporated into a microreactor and integrated into an online electrochemical sensing system (OECS), where it effectively eliminated common electrochemical interferences such as ascorbic acid, dopamine, and 3,4-dihydroxyphenylacetic acid during uric acid detection. This platform enabled continuous monitoring of uric acid fluctuations in rat brain tissue post ischemia–reperfusion injury.

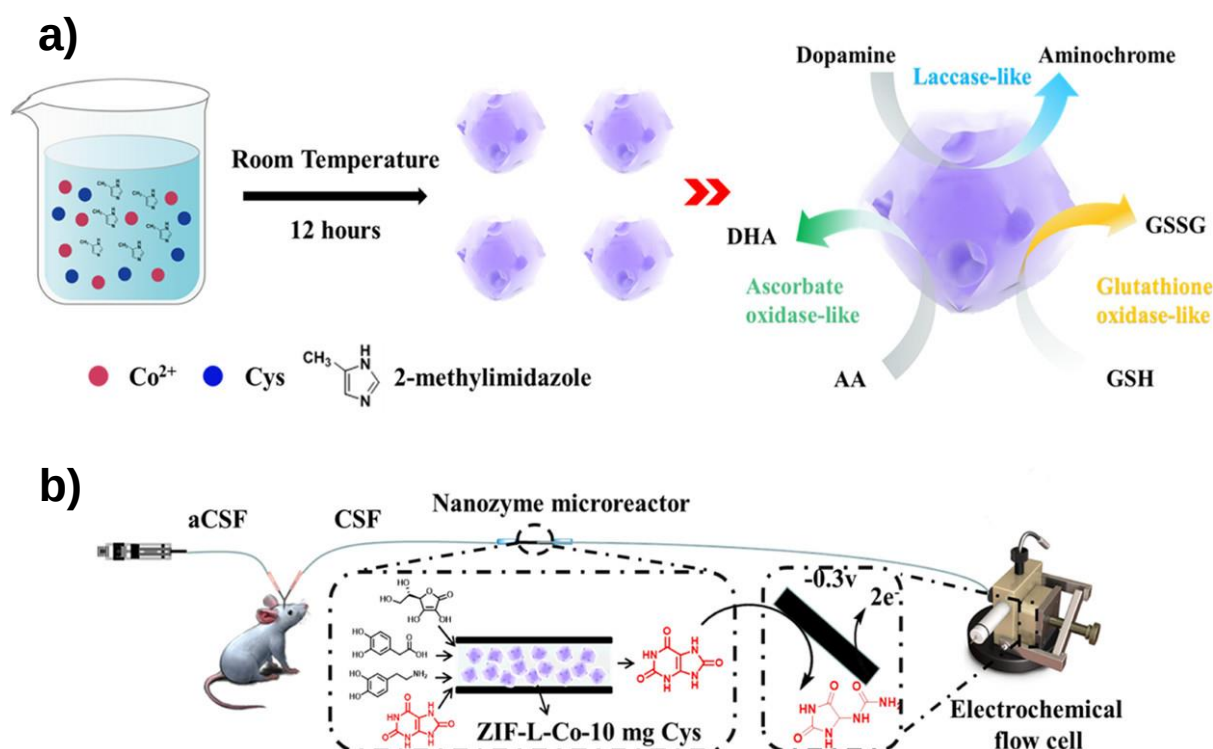


Figure 2. Schematic Illustration of (a) Synthesis and Properties of ZIF-L-Co-10 mg Cys and (b) Online Measurements of UA Based on a ZIF-L-Co-10 mg Cys-Immobilized Microreactor with Integration of In Vivo Microdialysis and Electrochemical Detection. Copyright 2021 ACS [60].

Nanozymes functional nanomaterials with enzyme-like activities hold promise across diverse applications but often suffer from suboptimal performance due to pH mismatch with their operating environments. To address this, a strategy was developed by Li et al., to tune the microenvironmental pH of MOF-based nanozymes by confining Brønsted polyacids or polybases within their pores [64]. Incorporating poly(acrylic acid) (PAA) into the channels of PCN-222-Fe shifted its local pH, optimizing peroxidase-like activity at physiological pH (7.4) and enabling compatibility with acid-sensitive oxidases in cascade systems (**Figure 3**). Both experimental data and molecular dynamics simulations confirmed that PAA contributes to proton donation and retention via hydronium–carboxylate salt bridges. Conversely, embedding poly(ethylene imine) increased the local pH, enhancing hydrolase-mimetic activity. This approach offers a generalizable method for improving nanozyme performance in real-world applications.

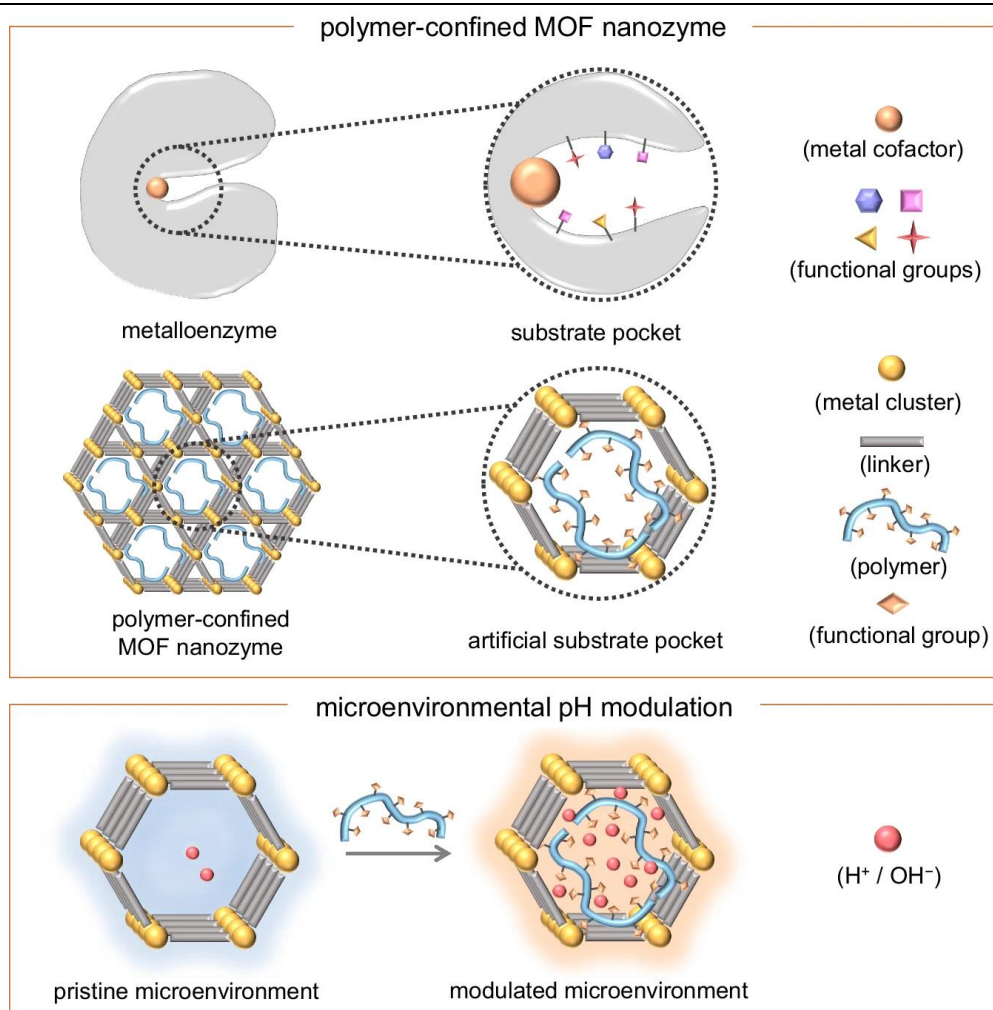


Figure 3. Breaking pH limitations of MOF nanozymes to boost their activities. Copyright 2024 Nature Communication [64].

In another study, the incorporation of Fe^{3+} into a cobalt-based MOF (Co-MOF) effectively alters the electronic environment of the framework, resulting in a bimetallic Co-Fe-MOF with significantly improved oxygen evolution reaction (OER) performance [65]. Synthesized via a one-step hydrothermal process using 2,2'-bipyridine-4,4'-dicarboxylic acid, various Co:Fe ratios were explored. The optimized Co-Fe-MOF (Co:Fe = 2:1) exhibited superior electrocatalytic activity with a low overpotential (310 mV at 10 mA cm⁻²), outperforming both monometallic counterparts and RuO₂. Thus, the alteration of central metal could be pivotal for enhancing catalytic properties in MOF-based nanozyme applications.

MOFs have emerged as promising peroxidase-mimicking nanozymes; however, their catalytic efficiency is often limited by restricted access to the metal centers, which are typically shielded by organic linkers. To overcome this challenge, a multimetallic nanoparticle-decorated MOF nanozyme, CuAuPt/Cu-TCP(Fe), was synthesized via an in situ approach [66]. The incorporation of Cu, Au, and Pt nanoparticles significantly enhanced the peroxidase-like activity by

lowering the energy barrier for hydroxyl radical ($\cdot\text{OH}$) generation during catalysis. This enhancement enabled the development of a sensitive colorimetric platform for the detection of hydrogen peroxide and glucose, achieving detection limits of $9.3\ \mu\text{M}$ and $4.0\ \mu\text{M}$, respectively. Moreover, a point-of-care testing (POCT) device was successfully fabricated by combining nanozyme test strips with a smartphone-based interface, demonstrating accurate glucose quantification in clinical serum samples, in agreement with conventional biochemical analyzers.

Beyond nanoparticle decoration, central metal doping within the MOF framework has also proven to be a powerful approach for improving catalytic performance [67]. By directly modifying the coordination environment of the metal centers, this strategy allows for enhanced electron transfer and increased exposure of active sites [68]. In this context, Shen et al. developed an amine-functionalized bimetallic Fe-Ni MOF-74 nanozyme (FeNi-MOF-74-NH₂) using a layered double hydroxide (LDH)-assisted synthesis, which combined metal intercalation and post-synthetic modification [69]. The synergistic interaction between Fe and Ni centers operated via a dual mechanism of electron transfer and hydroxyl radical generation, resulting in robust peroxidase-like behavior. This structurally optimized nanozyme enabled sensitive detection of a broad range of targets, including small biomolecules (e.g., H₂O₂, ascorbic acid), enzymes, and pathogenic bacteria such as *Staphylococcus aureus*.

Building upon the potential of MOF-based nanozymes, the integration of multiple functionalities into a single framework represents an advanced direction in biosensing applications. Chen et al. demonstrated this by developing a hybrid MOF system that couples peroxidase-like catalytic activity with red fluorescence emission in a Fe-doped PCN-222 framework (Fe@PCN-222) [70]. This dual-mode cascade sensing platform for glucose detection leveraged the catalytic role of Fe³⁺ ions to oxidize o-phenylenediamine (OPD), forming a fluorescent product (DAP) with emission at 566 nm in the presence of H₂O₂. Simultaneously, Fe@PCN-222 catalyzed the transformation of colorless TMB into the blue colored oxidized product (oxTMB), which showed a characteristic absorption peak at 652 nm. When combined with GOx, the system enabled dual mode detection with wide linear ranges and low detection limits $0.78\ \mu\text{M}$ in fluorescence and $2.41\ \mu\text{M}$ in colorimetry. The platform was also validated for reliable glucose sensing in real biological fluids such as human serum and saliva [69].

Therefore, tailoring metal centers within MOFs through doping, nanoparticle incorporation, and microenvironmental control significantly enhances nanozyme catalytic activity and specificity. These improvements enable sensitive detection of diverse biological targets and facilitate integration into practical diagnostic platforms, underscoring the promise of engineered MOF nanozymes for advanced biomedical applications.

3.2. Ligand Functionalization

Organic linkers can be chemically modified to introduce functional groups that enhance molecular recognition, improve electron transfer, or amplify signal outputs [71]. Functionalization with aptamers, antibodies, or zwitterionic groups enables selective binding to microbial biomarkers, while redox-active or fluorophore-modified ligands can facilitate signal transduction [72,73]. Thus, ligand engineering is crucial for integrating target specificity with catalytic amplification [74].

For example, Tolentino et al. engineered a multifunctional nanoscale platform by strategically functionalizing ZIF-8 ligands and encapsulating it within DNA-based surfactant micelles, forming nucleic acid nanocapsules (NANs) [75]. This ligand modification enabled efficient compartmentalization of both small molecules and biomacromolecules and allowed programmable degradation triggered by multiple stimuli (e.g., pH changes, enzymatic activity). The dual-gated regulation mechanism where both the MOF core and DNA shell independently control enzymatic activity and release kinetics resulted in enhanced molecular recognition and finely tunable catalytic behavior, thus improving biosensing and nanozyme applications under biologically relevant conditions.

Similarly, Shahrokhian et al. developed a highly sensitive electrochemical biosensor targeting *Escherichia coli* O157:H7 by functionalizing MOF ligands with amino groups, which facilitated stable immobilization of amine-modified aptamers via glutaraldehyde cross-linking [76]. The inclusion of conductive polyaniline within the MOF framework enhanced electron transfer, resulting in excellent electrochemical responses. This ligand-functionalized MOF platform exhibited a wide detection range (2.1×10^1 to 2.1×10^7 CFU mL⁻¹) and an impressively low detection limit of 2 CFU mL⁻¹, demonstrating the significant impact of ligand engineering on sensor sensitivity, specificity, and practical applicability for pathogen detection.

In another approach, Li et al. reported a dual MOF-on-MOF nanozyme system, CoNi-MOF@PCN-224/Fe, where ligand intercalation was used to anchor atomically dispersed active sites within the framework [77]. The tailored coordination environment created through ligand integration facilitated a Fenton-like catalytic mechanism, markedly boosting peroxidase-like activity by lowering the thermodynamic activation energy for hydrogen peroxide decomposition. This structural design enabled efficient electron transfer between the active moieties, resulting in a ~17-fold enhancement in electrochemiluminescence (ECL) intensity within the luminol–H₂O₂ system. The intercalated ligands also contributed to stabilizing the active centers, underscoring their vital role in catalytic amplification and sensitive biosensing applications.

Moreover, Ling et al. demonstrated the synthesis of an artificial nanozyme based on a metalloporphyrinic MOF (PMOF(Fe)), constructed through coordination of iron porphyrin ligands with Zr⁴⁺ ions [63]. The

intercalation of these metalloporphyrin ligands was instrumental in providing abundant and highly accessible Fe active sites that endowed the MOF with strong intrinsic peroxidase-like catalytic activity. To further enhance performance, ultrasmall platinum nanoparticles (Pt NPs) were anchored onto the PMOF(Fe) surface, where the strong interaction between the porphyrin-based ligand and Pt NPs promoted efficient electron transfer and catalytic synergy. This resulted in superior enzyme-mimicking activities, including catalase- and peroxidase-like functions, and high electrocatalytic sensitivity toward hydrogen peroxide and oxygen reduction reactions. This work highlights how strategic ligand integration within the MOF backbone can significantly enhance biosensing capability and provide a robust platform for the development of advanced MOF-based sensors.

Building upon the importance of ligand intercalation for improving nanozyme sensing capabilities, precise control over the morphology and size of MOFs is essential to optimize their catalytic activity and overall biosensing performance.

3.3. Morphology and Size Control

The physical dimensions and morphology of MOFs play a pivotal role in their biosensing performance [78]. Nanoscale MOFs with precisely controlled size and shape exhibit superior diffusion kinetics, enhanced surface reactivity, and improved contact with microbial analytes. These morphological features directly influence key parameters such as analyte loading, structural stability, and molecular interaction dynamics, making morphology control essential for developing rapid and sensitive biosensors [79].

To achieve such control, Usman et al. introduced a synthesis strategy to downsize MOF crystals to below 100 nm, which significantly improved their surface area, pore accessibility, and dispersibility in physiological environments factors critical for catalytic efficiency and biocompatibility [80]. These enhancements can be realized through both top-down and bottom-up approaches, including modulation of synthesis conditions (e.g., reaction time, temperature, and heating rate), ligand and solvent tuning, surface functionalization, and mechanical methods like grinding. These strategies influence the kinetics of MOF nucleation and growth, enabling uniform particle size distribution and high crystallinity. Tailoring these nanoscale features allows the development of MOFs with optimized reactivity, stability, and delivery for use in biomedical diagnostics and therapeutics.

Building on this, Singh et al. employed a one-step biomimetic mineralization approach to encapsulate enzymes such as glucose oxidase (GOx), OpdA, and α -chymotrypsin within ZIF-8 nanocrystals (**Figure 4**) [81]. The resulting ZIF-8@enzyme composites displayed uniform morphology and nanoscale dimensions, which significantly enhanced thermal stability and preserved enzyme functionality under stress conditions. Moreover, when used in electrochemical biosensors, these

composites facilitated efficient electron transfer, demonstrating their potential as robust nanozyme platforms with high sensitivity, operational stability, and selectivity in complex biological matrices.

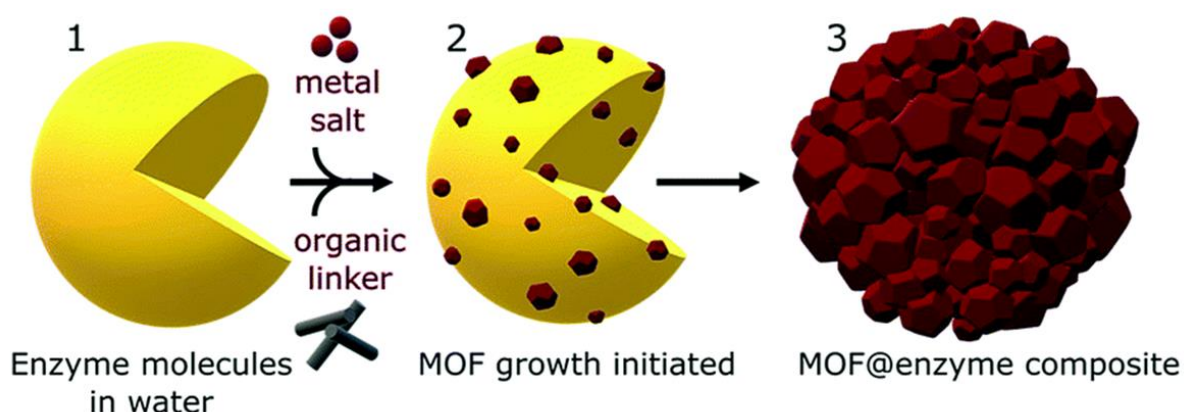


Figure 4. Schematic representing the biomimetic mineralised growth of ZIF-8 on enzymes. Copyright 2021 RSC [81].

In a parallel study, Nataraj et al. synthesized ZIF-67 using three different methods co-precipitation (ZIF-67-C), autoclaving (ZIF-67-A), and hydrothermal synthesis (ZIF-67-H) to develop a dual-mode sensor for acetaminophen detection [82]. Among the variants, ZIF-67-C exhibited the most favorable characteristics, including a uniform rhombic dodecahedral morphology and minimal aggregation, which contributed to superior electrocatalytic activity and peroxidase-like behavior. This morphology enhanced adsorption of 3,3',5,5'-tetramethylbenzidine (TMB) and hydroxyl radical ($\bullet\text{OH}$) generation from H_2O_2 , enabling efficient substrate oxidation and high signal output. ZIF-67-C achieved low detection limits ($0.014\ \mu\text{M}$ electrochemical, $0.034\ \mu\text{M}$ colorimetric) and demonstrated high recovery in real water samples, reinforcing the importance of morphology optimization for sensitive biosensing.

Further emphasizing morphology's role, Wang et al. reported a rapid synthesis of CdTe@ZIF-8 core-shell nanocomposites with controlled MOF morphology and pore size, enabling selective detection of small molecules like H_2O_2 while excluding larger biomolecules such as oxidase enzymes [83]. The uniform ZIF-8 shell functioned as a molecular sieve, allowing fluorescence quenching exclusively by small reaction products. This size-dependent selectivity enabled highly sensitive monitoring of enzymatic activity (e.g., uricase and GOx), highlighting the potential of morphology-engineered MOFs in microbial biosensing applications.

3.4. Composite and Hybrid Structures

The integration of MOFs with functional materials such as carbon nanotubes, graphene oxide, metal nanoparticles, and conductive polymers has emerged as a powerful strategy to overcome the inherent

limitations of pristine MOFs, including low conductivity and limited stability [84]. These hybrids often demonstrate improved signal transduction, environmental durability, and broader functionality, making them ideal candidates for developing robust and multifunctional microbial biosensors [27,85].

For instance, Chai et al. developed a MOF-on-MOF nanozyme (MOF-818@PMOF(Fe)) that combines catechol oxidase-like and peroxidase-like activities to enable cascade catalysis for dual-mode microbial biosensing [86]. In this system, MOF-818 produces H_2O_2 in situ, which is subsequently utilized by PMOF(Fe) to generate reactive oxygen species, amplifying both colorimetric and chemiluminescent signals (Figure 5). The spatial proximity and confinement between catalytic sites significantly enhance the overall efficiency. When coupled with a chlorpyrifos-specific aptamer, this hybrid nanozyme system enabled highly sensitive and selective pesticide detection, showcasing the potential of rationally designed hybrid nanozymes for multifunctional biosensing platforms.

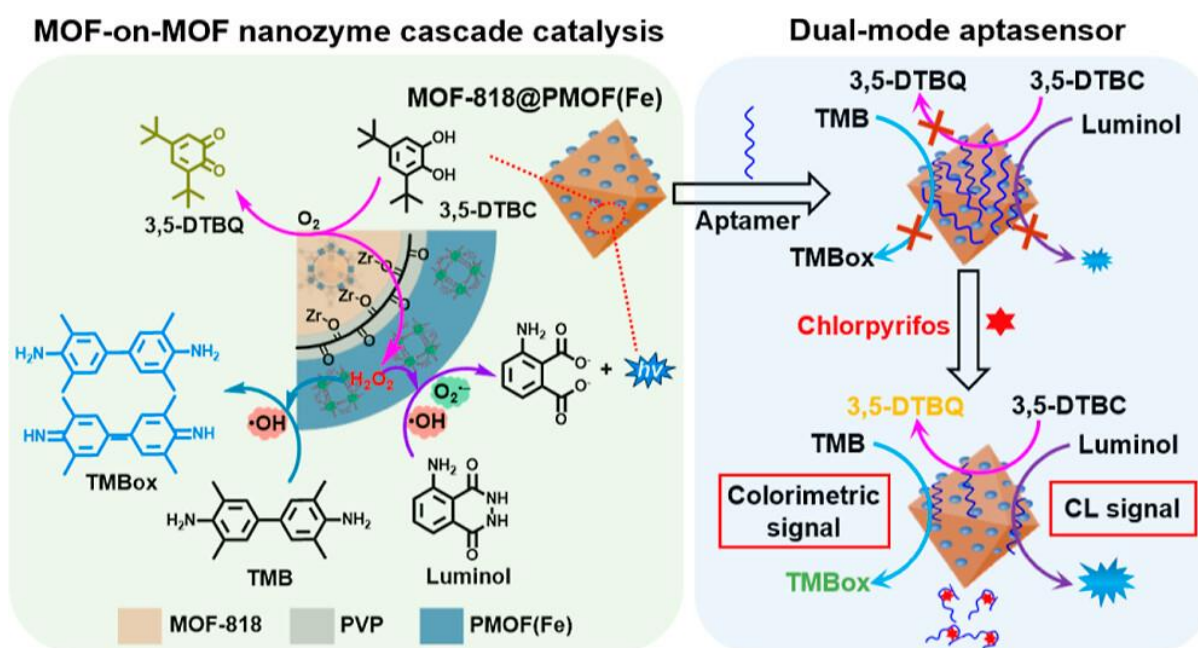


Figure 5. Illustration of catalytic mechanism and aptasensing application using a MOF-on-MOF nanozyme system. Copyright 2023 ACS [86].

In another example, Ma et al. reported a multifunctional electrochemical biosensing interface based on a three-dimensional gradient porous hollow fiber (GPF) membrane, which served simultaneously as a cell culture scaffold and sensing platform [87]. A composite of carbon nanotubes (CNTs) and MOF nanozymes was immobilized onto the GPF surface to fabricate a nonenzymatic electrode for real-time detection of hydrogen peroxide (H_2O_2) secreted by living cells (Figure 6). The MOF served as a peroxidase mimic offering higher stability than natural enzymes, while CNTs improved the electrical

conductivity and MOF dispersion by forming an interconnected 3D network. This synergistic structure enabled efficient electron transfer and enhanced catalytic performance, resulting in high sensitivity, selectivity, and long-term operational stability an ideal setup for metabolic monitoring and biomedical diagnostics.

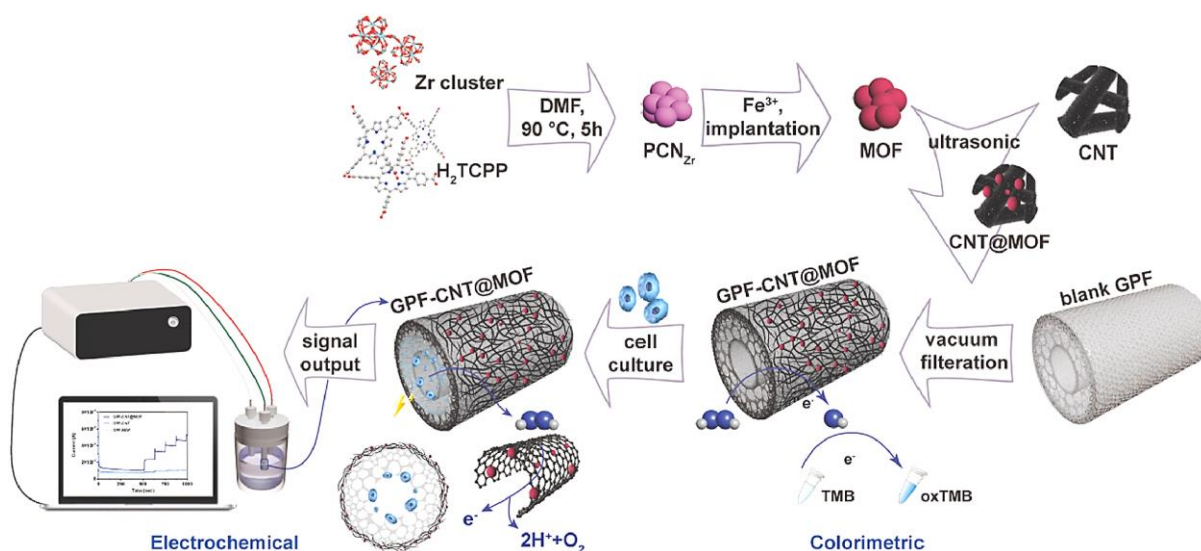


Figure 6. Schematic representation of the key steps in the fabrication of GPF-CNT@MOF electrodes and sensing principle. Copyright 2024 Elsevier [87].

Zhao et al. introduced a minimally invasive biosensor for uric acid (UA) detection using swellable hydrogel microneedles (MNs) that sample interstitial fluid [88]. The core sensing component was a DNAzyme@MOF composite, where DNAzyme integration significantly enhanced the peroxidase-like activity of the MOF. This hybrid configuration allowed for highly sensitive colorimetric detection of trace UA levels without relying on expensive or unstable natural enzymes. By combining DNAzyme functionality with MOF stability and catalytic activity, the system offered a rapid, painless, and user-friendly approach for clinical UA monitoring, demonstrating the biomedical potential of MOF-based nanozyme hybrids.

Guan et al. fabricated a multifunctional composite nanozyme (Fe₃O₄@Au/MOF) through self-assembly by incorporating Fe₃O₄ magnetic nanoparticles and Au nanoparticles into the MOF framework [89]. The magnetic Fe₃O₄ allowed recyclability, while the Au nanoparticles improved electron transport kinetics. This dual nanoparticle incorporation significantly boosted the peroxidase-like catalytic performance of the composite, enabling its application as an efficient enzyme-free electrochemical sensor for p-aminophenol detection. The resulting sensor exhibited a wide linear detection range, low detection limit (0.38 μmol/L), and excellent selectivity and stability, illustrating how nanoparticle incorporation enhances MOF-based nanozyme performance for biosensing.

Moreover, Tajwar et al. proposed a responsive hybrid system by integrating dual-stimuli-responsive poly(*N*-2-dimethylaminoethyl methacrylate) (PDM) onto a UiO-66-NH₂ MOF scaffold through in situ polymerization [90]. This configuration formed a flexible "soft cage" that encapsulated glucose oxidase (GOx) and horseradish peroxidase (HRP), providing a controlled microenvironment for enzymatic catalysis. The hybrid MOF/polymer system showed tunable catalytic behavior in response to pH and temperature and delivered an 8.9-fold enhancement in catalytic efficiency compared to free enzymes. This platform enabled a sensitive visual glucose detection assay in rat serum, highlighting the utility of MOF/polymer hybrids in enzyme stabilization and intelligent biosensing.

Therefore, through the strategic incorporation of functional nanomaterials and biomolecules, hybrid and composite MOF systems offer improved conductivity, catalytic efficiency, stability, and responsiveness key attributes for developing next-generation biosensors with high sensitivity, specificity, and operational robustness

4. Detection Mechanisms and Signal Transduction

The effectiveness of MOF nanozymes in microbial biosensing relies not only on their design but also on the detection mechanisms employed [91]. Signal transduction converts microbial presence into quantifiable outputs, and MOFs can facilitate this through catalytic reactions that generate optical, electrochemical, or fluorescent signals [92,93].

4.1. Colorimetric Detection

Colorimetric sensing leverages the catalytic oxidation of chromogenic substrates such as TMB (3,3',5,5'-tetramethylbenzidine) by MOF nanozymes in the presence of microbial analytes or their metabolic byproducts [94]. This method offers a simple, cost-effective, and visible output, suitable for point-of-care or field-based microbial detection.

Teymouri et al. developed a multifunctional intelligent film by homogeneously embedding a copper-based MOF (Cu-MOF) into an agar matrix, forming the Cu-MOF@AF film [95]. This film not only exhibited enhanced mechanical properties (e.g., stretchability, water resistance, and UV-blocking) but also showed potent antibacterial activity against *Escherichia coli* and *Staphylococcus aureus*. More importantly, the film served as a colorimetric sensor with a strong and irreversible response to volatile spoilage gases like hydrogen sulfide (H₂S) and ammonia (NH₃). Owing to the high surface area and active site availability of the Cu-MOF, the film achieved low limits of detection (LOD) and quantification (LOQ), while its dynamic and multi-hued color transitions allowed precise correlation with microbial spoilage indicators such as pH, total volatile basic nitrogen (TVB-N), and total viable count (TVC). Therefore, with this colorimetric platform, real-time monitoring of food freshness and microbial contamination could be achieved.

Likewise, Wang et al. designed a Cu-MOF nanoparticle (~550 nm) with intrinsic peroxidase-like activity that catalyzed the oxidation of 3,3',5,5'-tetramethylbenzidine (TMB) in the presence of hydrogen peroxide (H_2O_2), resulting in a visible yellow color change [96]. Functionalization of the MOF with surface-rich amine groups enabled aptamer conjugation specific to *Staphylococcus aureus*. The combination of aptamer-based molecular recognition and magnetic separation led to a selective and highly sensitive colorimetric detection method, highlighting the role of functionalized MOFs in targeted microbial diagnostics.

Further advancing this field, Ren et al. synthesized a two-dimensional cobalt-based MOF nanozyme (MVCM@ β -CD) with enhanced oxidase-like activity, achieved through modulation of the Co(III)/Co(II) ratio and surface functionalization with β -cyclodextrin (β -CD) [97]. This configuration increased surface interaction and catalytic efficiency, enabling the colorimetric detection of aminophenol isomers through oxidation-induced color changes. The nanozyme exhibited no background oxidation with 2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) alone (**Figure 7A**), but showed a strong visual response when catalyzing TMB (**Figure 7B**), with a low LOD of 0.16 μ M for m-aminophenol. These results confirmed MVCM@ β -CD as a potent candidate for rapid, low-cost, and label-free microbial sensing.

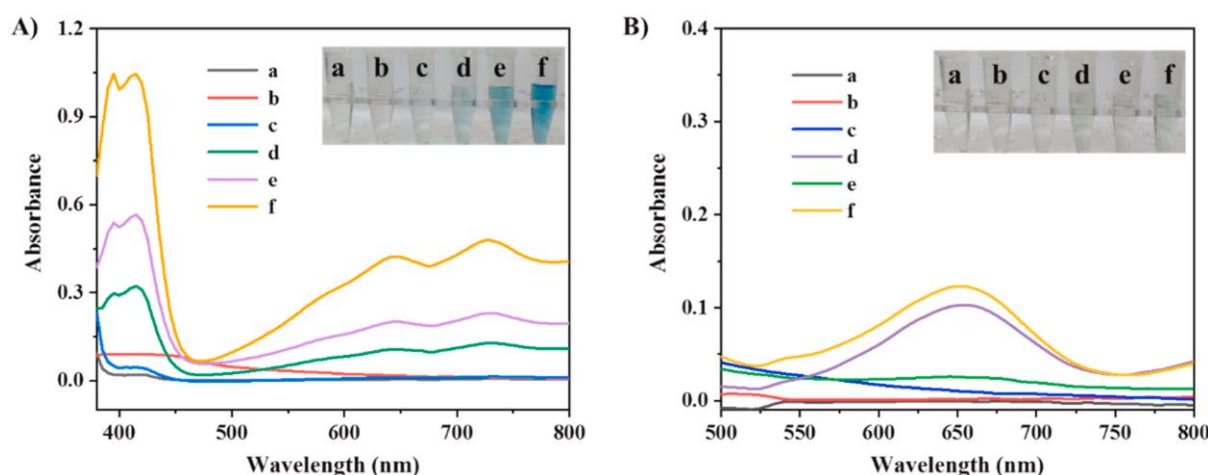


Figure 7. A) UV-Vis absorption spectra of a) ABTS, b) MVCM@ β -CD, c) ZIF-67 + ABTS, d) 2D Co-MOF + ABTS, e) MVCM + ABTS, f) MVCM@ β -CD + ABTS; B) UV-Vis absorption spectra of a) TMB, b) MVCM@ β -CD, c) ZIF-67 + TMB, d) 2D Co-MOF + TMB, e) MVCM + TMB, f) MVCM@ β -CD + TMB in NaAc-HAc buffer solution (pH = 3.0) incubated for 10 min at room temperature (Inset: pictures with corresponding colorimetric changes). Copyright 2023 Elsevier [97].

Li et al. employed a biological targeting strategy by immobilizing a temperate bacteriophage (SapYZUs8) onto a Cu-MOF nanozyme to detect viable *S. aureus* in food samples [98]. The resulting SapYZUs8@Cu-MOF hybrid enabled visual detection within 30 minutes and demonstrated high specificity and a low detection limit of 1.09×10^2

CFU/mL. The sensor remained effective even in complex matrices such as pork and milk, underscoring its applicability for real-world food safety monitoring.

To improve detection robustness, Wang et al. developed a dual-mode biosensor integrating both colorimetric and electrochemical outputs for the detection of *Vibrio parahaemolyticus* [99]. This sensor employed phenylboronic acid-modified CuO_2 nanodots embedded within a MOF (CP@MOF), which facilitated hydroxyl radical generation under acidic conditions, oxidizing TMB and producing a visible color change. The system also allowed Cu^{2+} ion-based electrochemical quantification, achieving a combined detection accuracy of 88.7%, thus offering an effective strategy for on-site seafood pathogen monitoring.

Expanding toward multidrug-resistant bacterial detection, Li et al. introduced a self-cascade nanozyme system by integrating Cu-functionalized MOF-808 and iron porphyrin MOF into a MOF@MOF hybrid [100]. This cascade system mimicked both catechol oxidase and peroxidase activities, enabling in situ H_2O_2 generation followed by amplified TMB oxidation (Figure 8). Coupled with specific aptamers, the system achieved ultrasensitive detection of Methicillin-resistant *S. aureus* (MRSA) and *Pseudomonas aeruginosa* with detection limits as low as 5 and 2 CFU/mL, respectively. The synergistic catalytic effect of the hybrid nanozyme provided a highly specific and sensitive tool for MDR bacteria monitoring in both clinical and food settings.

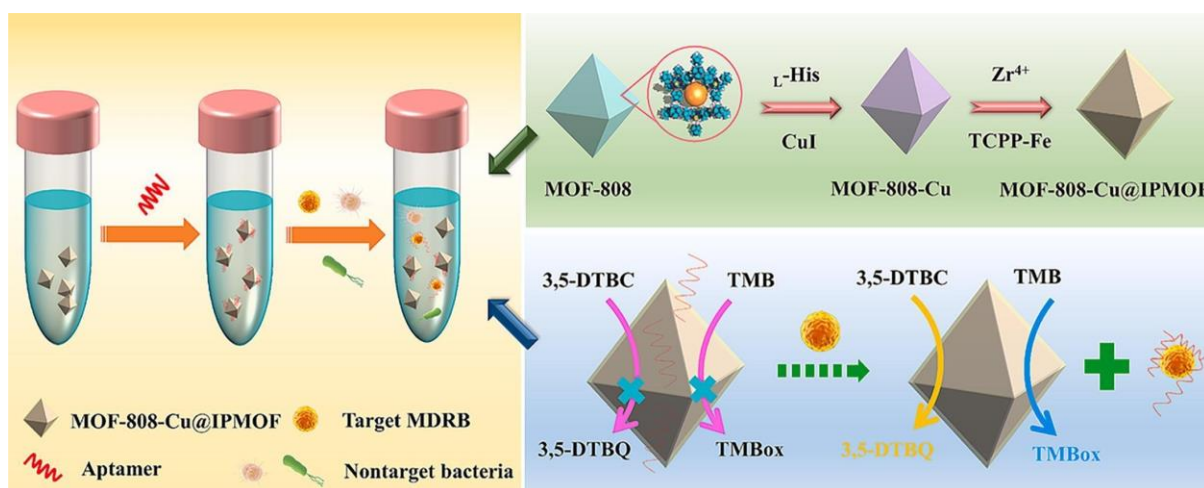


Figure 8. Typical process for colorimetric MDRB detection and sensing strategies. Copyright 2025 Elsevier [100].

Similarly, Hao et al. developed a 2D Ni–Co bimetallic MOF (2D-NCM) via in situ transformation of layered double hydroxides [101]. This material exhibited enhanced peroxidase-like activity and produced distinct, time-dependent absorbance changes upon interaction with different microbial species, including clinical pathogens and brewing fungi. The resulting multichannel detection profile enabled label-free,

wash-free microbial discrimination within 30 minutes, making it suitable for high-throughput diagnostics in clinical and food environments.

In addition, Liu et al. reported the development of a colorimetric enzyme-linked immunosensor using a Cu-hemin MOF with superior peroxidase-like activity for detecting the antibiotic furazolidone (FZD) [102]. This bimetallic MOF catalyzed H_2O_2 to generate hydroxyl radicals that oxidized TMB into a blue product detectable at 650 nm. The sensor demonstrated an ultra-low detection limit of 0.01 ng/mL and high specificity (<0.1% cross-reactivity), proving its effectiveness for antibiotic monitoring in food products.

Collectively, these studies underscore the versatility and efficacy of nanozyme-based MOFs in colorimetric microbial detection. By combining catalytic activity with molecular recognition (via aptamers or phages) and innovative sensor platforms (films, cascades, or dual-mode systems), MOF-based nanozymes offer rapid, sensitive, and field-deployable tools for pathogen monitoring in food safety, clinical diagnostics, and environmental surveillance.

4.2. Electrochemical Detection

Electrochemical biosensing represents a powerful and versatile approach for microbial detection, offering high sensitivity, real-time monitoring, and compatibility with miniaturized devices. This method utilizes the redox-active properties of metal–organic frameworks (MOFs) to transduce microbial interactions into measurable electrical signals, such as changes in current, voltage, or impedance [103,104]. Among recent advances, the integration of nanozyme-functionalized MOFs with electrochemical platforms has emerged as a promising strategy for enhancing microbial sensing performance.

Chen et al. developed a zinc-based MOF (Zn-MOF)-supported electrochemical sensing system, where metal nanoparticles (NPs) were electrodeposited onto Zn-MOFs with different morphologies to create a self-supported nanozyme platform [105]. Among the tested nanoparticles, silver (AgNPs) exhibited superior electrocatalytic activity for hydrogen peroxide (H_2O_2) reduction compared to platinum (PtNPs) and gold (AuNPs). The study further revealed that two-dimensional Zn-MOFs (2D Zn-MOFs) offered higher surface area, better conductivity, and improved metal dispersion compared to their three-dimensional counterparts (3D Zn-MOFs), resulting in enhanced electrochemical performance. The Ag/2D Zn-MOF-modified electrode demonstrated a low detection limit of 1.67 μM and a wide linear range from 5.0 μM to 70 mM for H_2O_2 detection (**Figure 9**). This system was successfully employed to monitor H_2O_2 released by both normal and tumor cells during drug stimulation, demonstrating the potential of MOF-based nanozymes for real-time microbial and cellular redox monitoring.

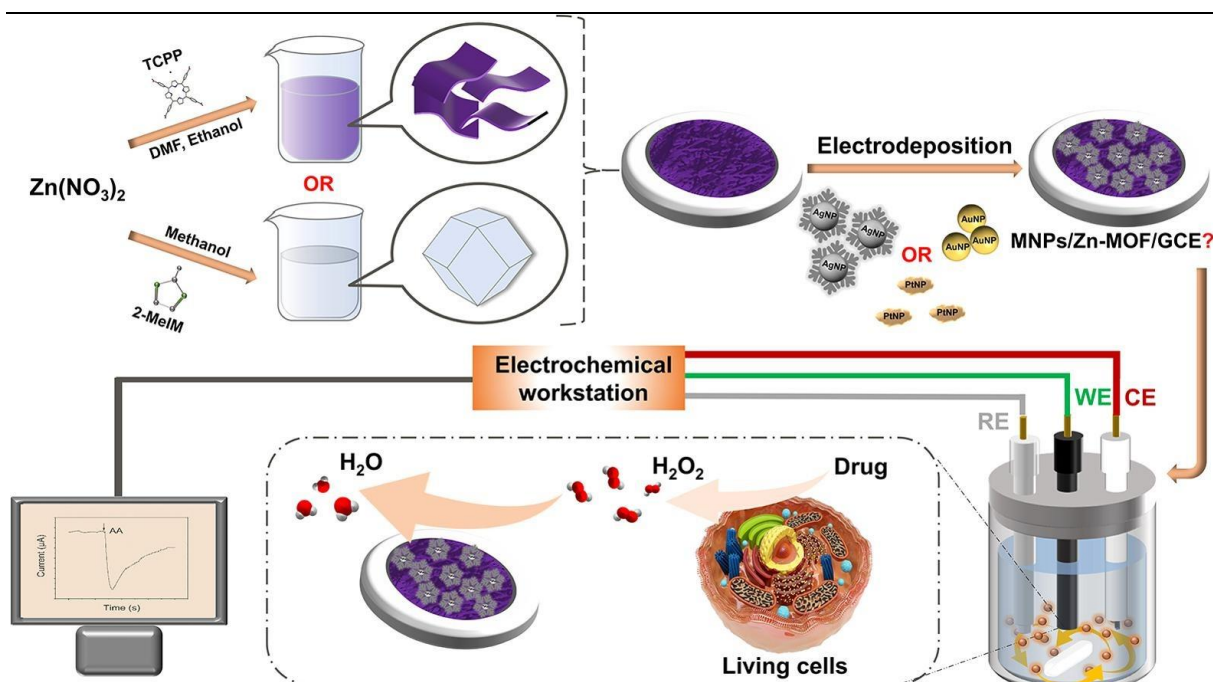


Figure 9. Schematic diagram of the major steps for fabricating MNPs/Zn-MOF modified electrodes and the H₂O₂ sensor used for in situ monitor of living cells-released H₂O₂ from upon the stimulation of drug and transfer data to the electrochemical station. Copyright 2022 Elsevier [105].

To address limitations posed by hypoxic and reductive environments common in bacterial infections namely low oxygen levels and high glutathione (GSH) concentrations Mo et al. designed a multifunctional nanozyme-based platform termed GATC [106]. This system integrates Cu-based MOF nanosheets with tannic acid-chelated gold nanoparticles (Au-TA) and G-quadruplex/hemin DNAzyme-aptamer probes. Among several MOF compositions, monometallic Cu-ZIFs showed superior catalytic and probe-loading efficiency over bimetallic alternatives such as CoCu-ZIF and ZnCu-ZIF. The hybrid system exhibited enhanced peroxidase (POD)-like activity for robust hydroxyl radical ($\bullet$ OH) production, along with catalase-like and GSH oxidase-like functionalities to alleviate hypoxia and minimize ROS scavenging, respectively. GATC enabled aptamer-mediated selective recognition of methicillin-resistant *Staphylococcus aureus* (MRSA), achieving potent antibacterial activity at low concentrations (3 μ g/mL). Furthermore, the platform supported both electrochemical and chromogenic detection modes, offering real-time monitoring of infection treatment. This multifunctional construct exemplifies the integration of detection and therapeutic functionalities into a single MOF-based nanozyme system.

In a related development, an innovative homogeneous voltammetric (HVC) sensing strategy was reported for detecting fluoroquinolone antibiotics (FQs), often used as markers of bacterial contamination or

residues [107]. The sensing system utilized iron-based MOF (Fe-MOF) nanozymes in combination with graphdiyne/carbon nanotube (GDY/CNT) composites to enhance signal output. In this design, Fe^{3+} ions on the Fe-MOF surface selectively chelated with carbonyl and carboxyl groups of FQs, triggering a Fenton-like reaction that increased peroxidase-mimicking activity and catalyzed the oxidation of o-phenylenediamine (OPD) to generate diaminophenazine (DAP), a redox-active product. The GDY/CNTs composite, offering high conductivity and surface reactivity, was immobilized on the electrode surface to further amplify the electrochemical signal. Using ciprofloxacin (Cip) as a model FQ, the system achieved a linear detection range from 20.0 to 2000.0 nM and a low detection limit of 8.3 nM. Comparable performance was obtained for other FQs, including enrofloxacin and levofloxacin, demonstrating the platform's suitability for electrochemical detection of microbial residues and related diagnostics.

Furthermore, Gao et al. reported an electrochemical platform specifically designed for the detection of H_2O_2 as a biomarker for microbial oxidative stress responses [108]. The system employed a synergistic hybrid of graphene (Gr) and MOF-on-MOF nanozymes composed of iron and copper (FeCu-NZs). Fe-MOFs were first synthesized via a solvothermal route, then decorated with Cu^{2+} ions to enhance their peroxidase-like catalytic efficiency. Integration with graphene further amplified the signal response due to improved conductivity. The FeCu-NZs-based sensor achieved a remarkable detection limit of 0.06 μM across a broad linear range (0.1–3800 μM) for H_2O_2 . In addition to its electrochemical capabilities, this system enabled complementary colorimetric detection via hydroxyl radical generation and TMB oxidation. Application to real samples showed high recovery rates (>95.7%), underlining its utility for microbial monitoring in complex biological or environmental matrices. Given that H_2O_2 is a critical marker in host-pathogen interactions, especially under inflammatory or infection conditions, this system holds promise for diagnostic applications in microbiology and medicine.

Beyond electrochemical sensing, nanozyme MOFs also enable fluorescence and luminescence-based microbial detection, offering high sensitivity and visual readouts. The following section outlines key advances in this area.

4.3. Fluorescence and Luminescence

MOFs with intrinsic fluorescence or those functionalized with luminescent dyes have emerged as powerful platforms for microbial and biochemical sensing [109]. These nanozyme-type MOFs exhibit enzyme-mimicking activities alongside optical responsiveness, enabling dual-mode detection through fluorescence and chemiluminescence [110]. Their unique architectures allow for responsive signal modulation typically fluorescence enhancement or quenching upon specific microbial interactions or enzymatic activity, offering highly sensitive and selective

detection routes with potential applications in biomedical diagnostics, environmental monitoring, and food safety [111–113].

Yi et al. developed a bifunctional nanozyme composed of cobalt-doped carbon dots encapsulated within a porphyrinic MOF (Co-CD/PMOF), which demonstrated strong peroxidase-like activity and intrinsic fluorescence for dual-mode detection of aflatoxin B1 (AFB1) [114]. This system enabled both chemiluminescence (CL) and fluorescence (FL) immunoassays: the CL mode utilized luminol/H₂O₂ catalysis via reactive oxygen species ($\bullet$ OH, O₂ $\bullet^-$, ¹O₂) for glow-type emission, achieving a detection limit of 0.217 ng/mL, while the FL-based sandwich immunoassay reached a more sensitive 0.027 ng/mL. Similarly, a copper-based nanozymic MOF (Cu-MOF) with peroxidase-like and fluorescent properties was used to construct a dual-mode, label-free aptasensor for thrombin, a key COVID-19 biomarker [115]. The sensor exploited single-stranded DNA (ssDNA) aptamers that quenched the MOF's fluorescence and enzymatic activity, which were restored upon thrombin binding. This turn-on sensing strategy enabled thrombin detection at 350 pM (colorimetry) and 110 fM (fluorescence), with over 95% recovery in patient samples within 45 minutes, highlighting its feasibility for point-of-care diagnostics.

Expanding beyond biomarker detection, Zhu et al. reported a ratiometric fluorescence sensor for sulfide ions (S²⁻) using an NH₂-functionalized Cu-MOF (**Figure 10**) [116]. The MOF's ligand contributed blue fluorescence (λ_{em} = 435 nm), while its Cu²⁺ centers catalyzed oxidation of o-phenylenediamine (OPD) into oxOPD (λ_{em} = 570 nm). S²⁻ inhibited this process by forming CuS, reducing oxOPD fluorescence and enhancing native emission, resulting in a dual-emission shift that allowed for ultrasensitive S²⁻ detection down to 0.1 μ M in food samples. Addressing biofilm-related challenges, Liu et al. synthesized Ce-based MOF nanozymes with dual DNase- and peroxidase-like activities [117]. The Ce(IV) complex degraded extracellular DNA (eDNA), a key structural biofilm component, while the MOF catalyzed H₂O₂ to eliminate released bacteria. This synergistic system effectively disrupted biofilms, inhibited bacterial recolonization, and promoted wound healing in vivo underscoring nanozyme-MOFs' therapeutic potential.

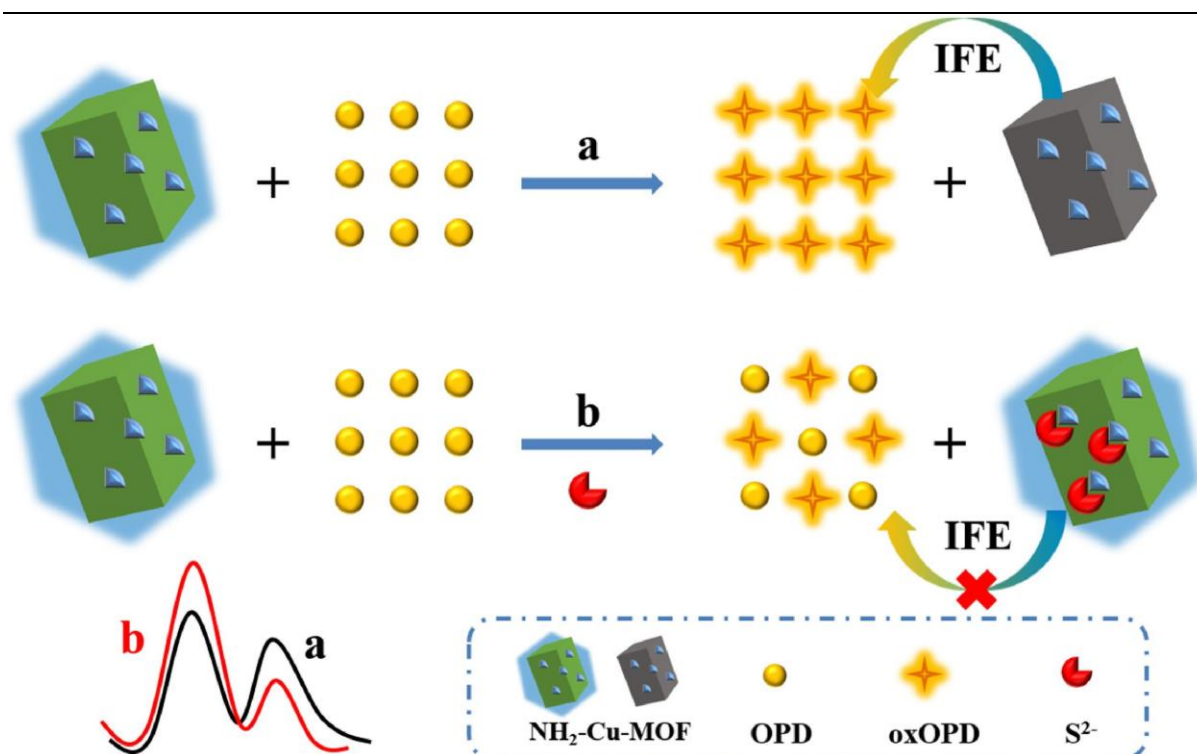


Figure 10. Schematic illustration for S^{2-} detection with bifunctional MOF. Copyright 2023 Elsevier [116].

In another application, Chen et al. developed a Cu@MOF-based fluorescence sensor for alkaline phosphatase (ALP) [118]. The MOF exhibited strong fluorescence ($\lambda_{em} = 444$ nm) and oxidase-like activity that oxidized p-phenylenediamine (PPD), forming PPDo_x, which quenched the MOF's fluorescence via the inner filter effect (IFE). The presence of ATP inhibited this process by chelating Cu^{2+} , while ALP hydrolyzed ATP, restoring both fluorescence and enzymatic activity. This system achieved a 0.14 U/L detection limit, suitable for serum ALP monitoring and inhibitor screening. Similarly, Hou et al. reported a ratiometric fluorescence system based on a bifunctional Cu(II)-MOF for detecting pyrophosphate (PPi) and pyrophosphatase (PPase) activity [119]. PPi inhibited the MOF's activity via Cu^{2+} binding, while PPase hydrolyzed PPi to Pi, reactivating peroxidase-like function and enabling OPD oxidation into fluorescent DAP. Förster resonance energy transfer (FRET) between the MOF and DAP allowed detection of PPase down to 0.30 mU/mL and PPi at 0.53 μ mol/L.

Ye et al. demonstrated a MOF nanozyme sensor for tetracycline detection using a hemin-loaded MOF with both intrinsic fluorescence and peroxidase-mimicking activity [120]. Tetracycline enhanced peroxidase catalysis via π - π stacking with confined hemin, oxidizing TMB to a dark blue product. Concurrently, tetracycline aggregation triggered green fluorescence ($\lambda_{em} = 535$ nm), while quenching the MOF's native blue emission ($\lambda_{em} = 425$ nm) via IFE. This enabled ratiometric fluorescence sensing (F_{535}/F_{425}), achieving detection limits of 27.2 nM (colorimetric) and

4.1 nM (fluorescent), showcasing excellent selectivity and on-site application potential. Therefore, nanozyme-based MOFs offer greater potential for structural modification, enabling the development of high-performance, multifunctional biosensors for microbial detection.

5. Biomedical Applications

In biomedical contexts, rapid and accurate detection of pathogenic microbes is critical for early diagnosis, infection control, and treatment monitoring [121]. MOF nanozymes offer significant promise due to their tunable biorecognition capabilities and efficient signal generation [122].

5.1. Pathogen Detection in Clinical Samples

The rapid and accurate detection of clinically relevant bacteria including *Escherichia coli*, *Staphylococcus aureus*, and multidrug-resistant strains such as methicillin-resistant *Staphylococcus aureus* (MRSA) remains a significant challenge in clinical diagnostics [123]. MOF-based nanozymes have emerged as promising platforms due to their tunable surface chemistry, high surface area, and catalytic capabilities. These features allow them to be engineered for selective recognition of microbial biomarkers or toxins, enabling rapid and sensitive detection in various clinical matrices such as blood, urine, saliva, and wound exudates [124]. Moreover, their compatibility with existing clinical workflows facilitates early disease diagnosis and timely therapeutic intervention [125].

The global rise in antimicrobial resistance, particularly among pathogens like MRSA, underscores the urgent need for advanced diagnostic and therapeutic technologies. Traditional antibiotics such as vancomycin are increasingly undermined by bacterial adaptations, including metabolic tolerance mechanisms driven by the accumulation of toxic byproducts. To address these issues, Wang et al. developed a multifunctional gallium/copper-based MOF (Ga/Cu-MOF) nanozyme designed for both pathogen detection and eradication [126]. This nanozyme leverages the structural advantages of MOFs to co-deliver antibiotics and release Ga^{3+} and Cu^{2+} ions in a controlled manner. These ions disrupt bacterial metabolism by suppressing nitric oxide synthesis and promoting degradation of S-nitrosothiols, thereby weakening the bacteria's stress response systems. It not only enhances antibiotic susceptibility but also induces programmed bacterial cell death via ferroptosis and cuproptosis. The Ga/Cu-MOF nanozyme also demonstrated excellent antibacterial activity by disrupting biofilms and eliminating intracellular bacteria residing within host immune cells. When tested in clinically relevant infection models, including skin wounds and osteomyelitis, the nanozyme effectively reduced bacterial burden, mitigated inflammation, and promoted tissue healing highlighting its potential for integrated diagnostic and therapeutic applications in infectious disease management.

To overcome limitations in traditional lateral flow assays (LFAs) such as low sensitivity and the need for amplification steps Li et al. designed a next-generation detection platform by combining a rationally engineered multivalent aptamer (multi-Apt) targeting *S. aureus* with a multifunctional nanozyme, $\text{Fe}_3\text{O}_4@\text{MOF}@\text{PtPd}$, functionalized with vancomycin [127]. The optimized aptamer significantly improved binding affinity (from 135.9 nM to 16.77 nM), and the resulting MA-MN LFA system enabled magnetic capture, signal amplification, and simplified detection of *S. aureus* (Figure 11). This ternary complex-based assay achieved ultra-sensitive detection, with a limit of just 2 CFU/mL and a dynamic range spanning from 10 to 1×10^8 CFU/mL all within 30 minutes. Its simplicity, speed, and high specificity make it well-suited for real-time clinical diagnostics, particularly for Gram-positive bacterial infections. Together, these advances underscore the versatility and promise of MOF-based nanozyme platforms in the clinical setting not only for rapid and accurate pathogen detection but also for integrated antimicrobial strategies that address both diagnosis and treatment in the era of rising antibiotic resistance.

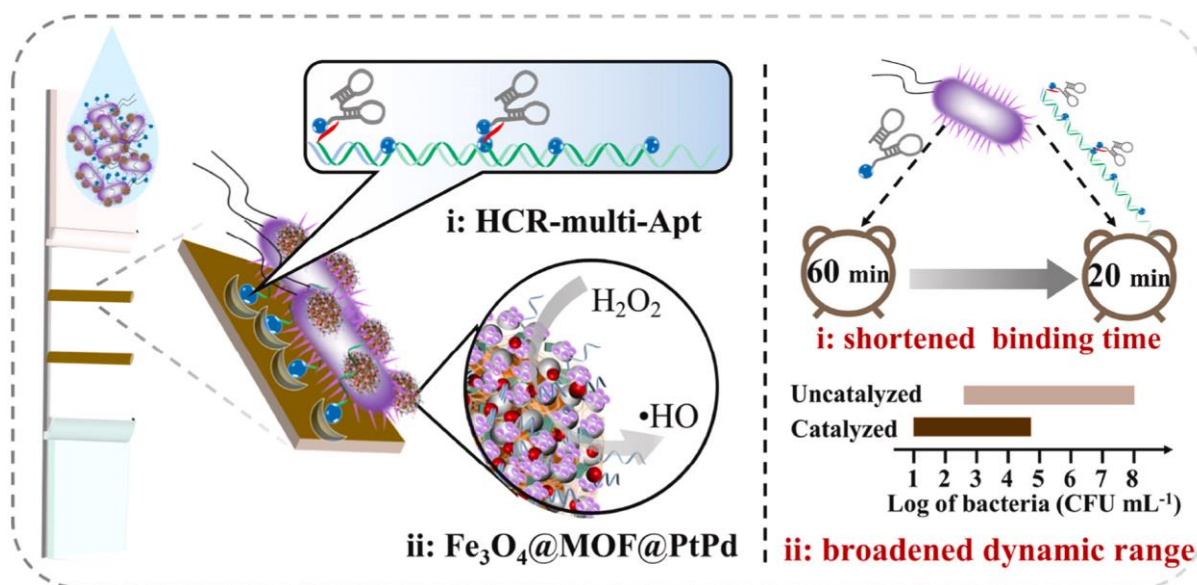


Figure 11. Schematic diagram of the assembly of HCR-multi-Apt and bacteria detection. Copyright 2024 Elsevier [127].

5.2. Real-Time and Point-of-Care Diagnostics

The development of portable, user-friendly biosensors is vital for decentralized healthcare [128]. MOF nanozymes enable real-time monitoring through catalytic reactions that produce immediate colorimetric or electrochemical signals [129]. These sensors are especially

valuable in resource-limited settings or during outbreaks where rapid screening is essential.

Bacterial infections remain a major public health concern, necessitating rapid and highly sensitive diagnostic tools for timely intervention. To address this, Ren et al. reported a smart, dual-mode biosensor has been developed using nanozyme-based MOFs for point-of-care detection of pathogenic bacteria [130]. This innovative sensor integrates a surface-enhanced Raman scattering (SERS) platform with oxidase-like nanozyme activity, enabling both colorimetric and spectroscopic detection. The system comprises two key components: an iron oxide nanoparticle-based capture module functionalized with specific aptamers for bacterial recognition and enrichment, and a signal module composed of mesoporous MnO_2 nanozymes loaded with plasmonic gold nanoparticles. Functionalized with concanavalin A, the signal module creates strong SERS hotspots and catalyzes the oxidation of non-SERS-active TMB into a highly active oxTMB form, producing both a strong Raman signal and a visible color change. This dual readout enhances detection reliability, with limits as low as 7 CFU/mL for SERS and 30 CFU/mL for colorimetric analysis. The sensor demonstrates excellent specificity for *Staphylococcus aureus* and performs effectively in complex clinical samples such as sepsis-infected blood. These features underscore the promise of nanozyme MOF-based smart sensors for real-time, on-site microbial diagnostics in clinical applications.

Access to clean water is vital for human health, yet underdeveloped regions and emergency scenarios often lack efficient, low-energy water purification methods. To address this challenge, Fu et al. reported a novel class of portable disinfection materials has been developed by integrating Fe-MIL-101 nanozyme metal–organic frameworks (MOFs) onto flexible carboxymethyl cellulose substrates (e.g., filter paper, cotton, gauze) through in-situ cross-linking growth [131]. These Fe-MIL-101@fiber composites function as point-of-use (POU) water disinfection modules, offering strong antibacterial activity, ease of transport, and biosafety (**Figure 12**). Among them, the Fe-MIL-101@carboxymethyl filter paper (Fe-MIL-101@CMFP) demonstrated exceptional performance, maintaining structural integrity and filtration efficiency even after 200 cycles of manual or mechanical stress. The composite exhibits robust oxidase- and peroxidase-mimicking activity, producing reactive oxygen species (ROS) such as hydroxyl radicals ($\bullet\text{OH}$) and superoxide ($\text{O}_2\bullet^-$), which enable rapid and efficient bacterial elimination (~99%). Notably, the material is effective against microbes present in real field water without inducing biosafety concerns. These flexible, nanozyme-powered MOF composites show great promise for decentralized microbial disinfection, offering a practical and safe solution for water sterilization in resource-limited or emergency healthcare settings.

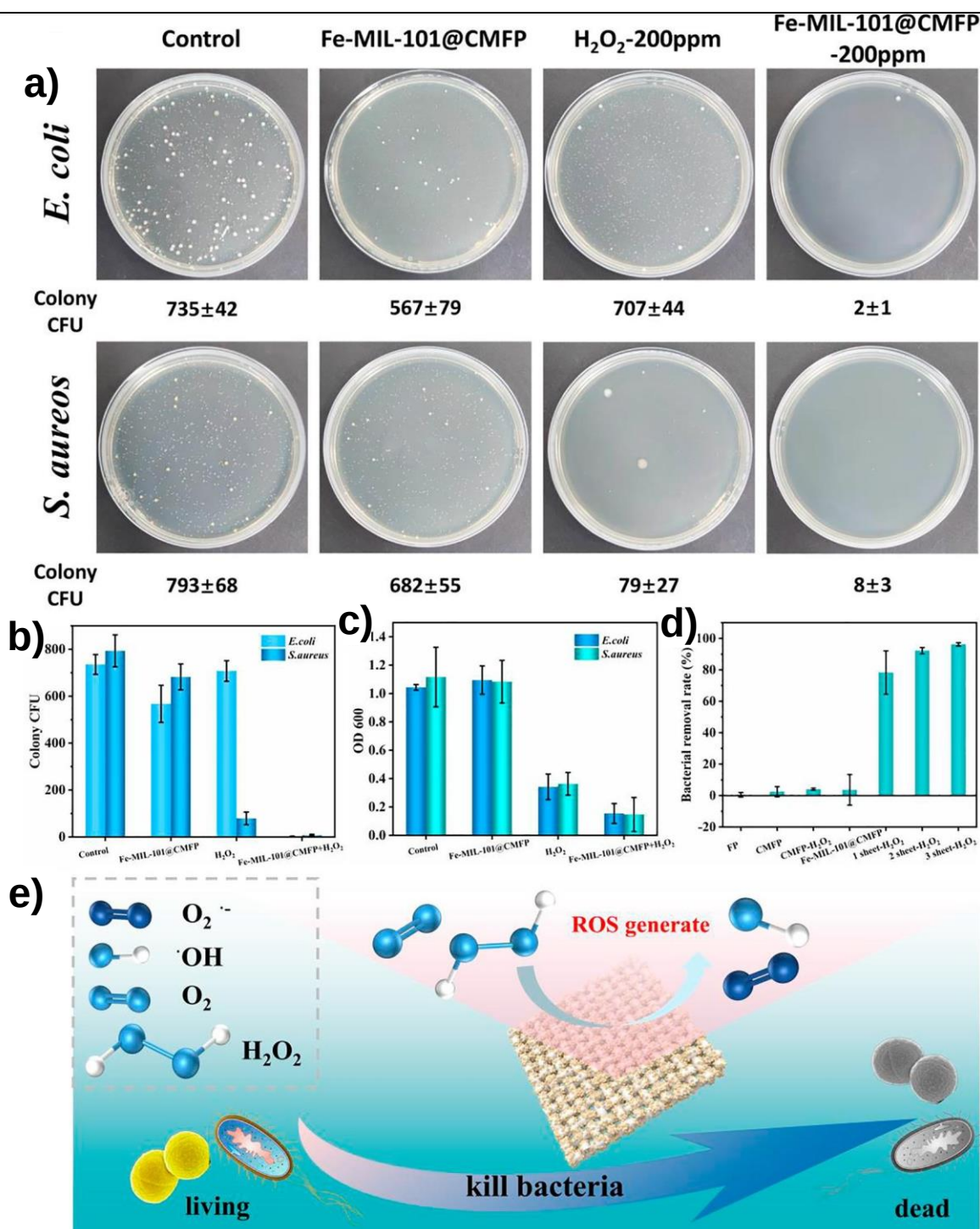


Figure 12. (a) Agar plate culture results of bacteria treated with Fe-MIL-101@CMFP. (b) Plate colony count. (c) OD600 test result of filtrate for 12 h. (d) Sterilization performance of each filter paper material in filtration. (e) Kill bacteria schematic diagram. Copyright 2024 Elsevier [131].

The need for sensitive, portable, and non-invasive methods to detect pathogenic bacteria is crucial for point-of-care diagnostics. Feng et al. reported an advanced electrochemiluminescence (ECL) biosensor by combining a flexible paper-based sensor with a disposable three-

electrode detection system. The cellulose paper was functionalized to specifically respond to *Staphylococcus aureus* (*S. aureus*) by using an aptamer as the recognition element and a probe DNA linked to glucose oxidase (probe DNA-GOD) for signal amplification [132]. When the aptamer binds to *S. aureus*, it triggers the controlled release of probe DNA-GOD. The residual probe DNA-GOD on the paper sensor reacts with glucose, causing a notable decrease in the ECL signal. To enhance the biosensor's ECL performance, numerous $\text{Ru}(\text{bpy})_3^{2+}$ molecules were incorporated into porous zinc-based metal-organic frameworks (MOFs) to create $\text{Ru}(\text{bpy})_3^{2+}$ -functionalized MOF nanoflowers (Ru-MOF-5 NFs). This biosensor allows for precise, non-destructive, and real-time detection of *S. aureus* contamination in food samples, offering a novel approach for sensitive bacterial identification.

5.3. Wound Monitoring and Infection Control

Chronic wounds, particularly in diabetic patients, are highly susceptible to microbial colonization and persistent infections, which significantly impede the healing process and increase the risk of complications [133]. These infections are often compounded by the presence of bacterial biofilms and rising antibiotic resistance, necessitating the development of multifunctional wound care systems capable of both real-time infection monitoring and active therapeutic intervention [134]. When integrated into wound dressings or hydrogels, MOF nanozymes can provide a dual function sensing infection-associated biomarkers such as hydrogen peroxide (H_2O_2) or glutathione, and simultaneously catalyzing therapeutic reactions that neutralize pathogens and oxidative stress [135].

A notable example of such a multifunctional platform is the nanozyme reported by Zhao et al., in which gold nanoclusters (Au NCs) were anchored onto zirconium-based porphyrin MOFs (Au NCs@PCN) via in situ growth [136]. The resulting hybrid nanozyme exhibited both strong reactive oxygen species (ROS) generation and photothermal effects under near-infrared (NIR) irradiation, achieving localized heating up to 56.2°C . This synergistic response enabled efficient bacterial membrane disruption and protein leakage, with bactericidal rates of 95.3% against methicillin-resistant *Staphylococcus aureus* (MRSA) and 90.6% against ampicillin-resistant *Escherichia coli*. Moreover, in diabetic wound models, Au NCs@PCN treatment significantly accelerated healing, reducing wound size to just 2.7% within 21 days. Immunoblot analysis further demonstrated increased expression of angiogenic and epithelial proliferation markers, highlighting the platform's regenerative potential.

Building on this concept, Ren et al. developed a peroxidase-mimicking nanozyme by integrating Au NCs into a zeolitic imidazolate framework (Au@ZIF-8) [137]. This nanozyme exhibited enhanced peroxidase-like activity and photothermal effects upon NIR exposure,

leading to effective bacterial membrane disruption (66.3%) and MRSA clearance (up to 97%). The platform catalyzed the conversion of endogenous H_2O_2 into hydroxyl radicals ($\bullet OH$), facilitating both bacterial eradication and biofilm degradation (Figure 13). In vivo application of Au@ZIF-8 resulted in a remarkable wound closure rate of 97.4%, underscoring its suitability for chronic wound care where biofilm-associated infections are prevalent.

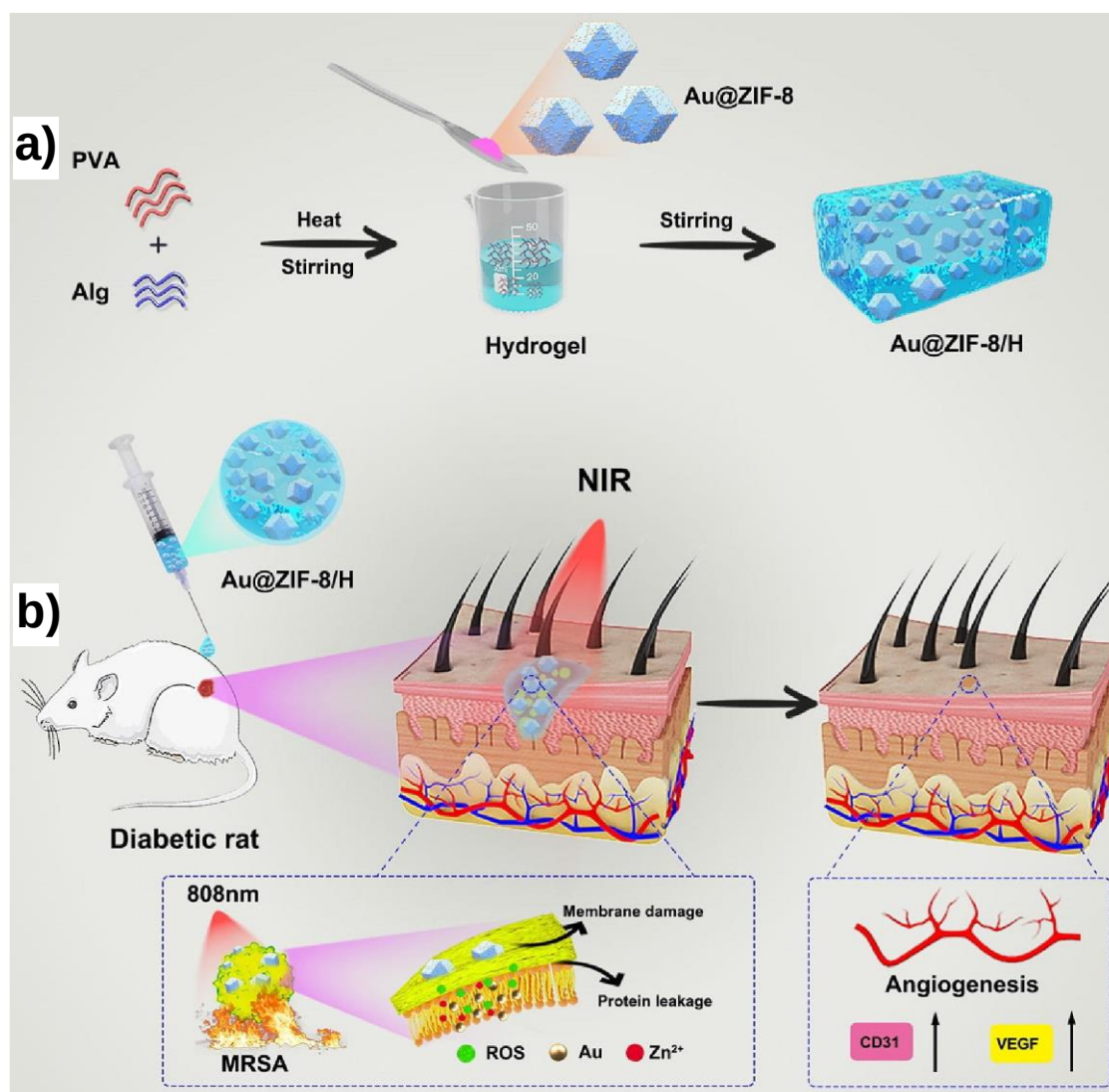


Figure 13. (a) Schematic process of synthesis Au@ZIF-8/H composite; (b) The process of bactericidal and stimulating cellular behavior, promoting skin cell regeneration and actively participating in epidermal regeneration to accelerate the healing of diabetic infected wounds. Copyright 2023 Elsevier [137].

Addressing another critical aspect of wound healing oxidative stress, Chao et al. proposed a smart antioxidative hydrogel system (MOF/Gel) comprising a MOF nanozyme embedded in a biocompatible gel matrix [138]. The nanozyme mimicked the activity of natural antioxidant enzymes, continuously scavenging excess ROS and restoring

redox homeostasis. This biochemical regulation facilitated the transition of the wound environment from an inflammatory to a proliferative phase, leading to enhanced tissue regeneration. In comparative studies, a single application of MOF/Gel demonstrated healing efficacy comparable to clinically used epidermal growth factor (EGF) gels, further validating its therapeutic potential.

In parallel, to combat the increasing threat of antibiotic resistance, Liu et al. engineered an antibiotic-free nanozyme system by growing ultrasmall gold nanoparticles in situ on MOF-stabilized Fe_3O_4 nanoparticles ($\text{Fe}_3\text{O}_4\text{@MOF@Au}$, or FMA NPs) [139]. These hybrid nanozymes exhibited robust peroxidase-like activity even at low H_2O_2 concentrations (0.97 mM), producing bactericidal $\bullet\text{OH}$ radicals. The FMA NPs showed strong antibacterial efficacy against both Gram-positive and Gram-negative bacteria, with excellent biocompatibility. In vivo studies confirmed their wound healing acceleration capabilities, demonstrating that MOF-based nanozymes can effectively circumvent the limitations of conventional antibiotics.

In addition to therapeutic efficacy, real-time infection monitoring is crucial for timely clinical intervention. Le et al. addressed this need by developing a dual-functional hydrogel composed of lysozyme-based hemin-loaded nanoparticles (Ly@He NPs) co-encapsulated with silver nitrate (AgNO_3) in a double-network hydrogel matrix of gelatin and polyvinyl alcohol [140]. This system combined sustained antibacterial action mediated by silver ion release and nanozyme-catalyzed ROS production with colorimetric biosensing capabilities. Specifically, the peroxidase-like activity of Ly@He NPs enabled the hydrogel to detect glutathione, a bacterial infection biomarker, via visible color change. Both in vitro and in vivo results validated the hydrogel's dual functionality in infection control and dynamic infection monitoring, paving the way for the next generation of smart wound dressings that integrate diagnostics with on-demand therapy. Therefore, by integrating catalytic activity with infection-responsive sensing and therapeutic features, these advanced materials offer a multifaceted solution to the pressing challenges of wound healing, especially in the context of diabetic ulcers and drug-resistant infections.

6. Environmental Applications

Environmental monitoring of microbial contamination is vital for water safety, air quality, and soil health. MOF nanozyme-based sensors offer portable, selective, and rapid detection solutions that can be deployed in diverse ecological settings. This section explores how these systems are adapted for environmental biosensing.

6.1. Waterborne Pathogen Detection

Waterborne pathogens such as *Escherichia coli*, *Salmonella*, and *Legionella* are major contributors to drinking water contamination, posing severe public health risks and environmental concerns [141]. Early and reliable detection of these pathogens is vital to prevent outbreaks and ensure safe water supplies. Traditional culture-based microbiological methods are often inadequate due to their slow turnaround time and inability to detect viable but non-culturable (VBNC) organisms. While molecular techniques such as RT-PCR and ELISA offer improved sensitivity, they are generally labor-intensive, costly, and not well-suited for on-site or field-based applications [142].

To overcome these limitations, nanozyme-based metal–organic frameworks (MOFs) have emerged as promising tools for waterborne pathogen detection. These hybrid materials combine the high surface area, porosity, and chemical tunability of MOFs with the catalytic (enzyme-like) activity of nanozymes, thereby facilitating efficient signal amplification in biosensing platforms [143]. MOF-based nanozymes have been effectively integrated into optical and electrochemical sensors, enabling rapid, sensitive, and cost-effective detection of pathogens such as *E. coli* O157:H7 in contaminated water. Their compatibility with portable systems, including smartphone-based readouts, further enhances their applicability for point-of-care and real-time environmental monitoring.

An illustrative example of this potential is the work by Magar et al., who developed a portable biosensing platform for the rapid and selective detection of *Staphylococcus aureus*, a common waterborne and foodborne pathogen [144]. This system employed copper-based MOFs (Cu-MOFs) integrated with gold nanoparticles (AuNPs) and mercaptopropionic acid (MPA) to immobilize specific antibodies onto a screen-printed electrode (SPE). The resulting disposable sensor (anti-*S. aureus*@MPA/AuNPs-Cu-MOF@SPE) demonstrated a broad detection range from 10 to 10⁷ CFU/mL and a low detection limit of 0.132 CFU/mL, with high selectivity against non-target bacteria. Impressively, the entire sensing process was completed within 20 minutes, showcasing its effectiveness for on-site pathogen detection in water samples.

In another notable study, Zhao et al. synthesized a europium-based MOF, [Eu(DHBDC)_{1.5}(DMF)₂]·DMF, which exhibited high thermal and water stability along with ligand-based fluorescence at 506 nm [145]. Although the material lacked initial Eu³⁺-centered emission due to an energy mismatch with the ligand (2,5-dihydroxyterephthalic acid, DHBDC²⁻), the introduction of 2,6-pyridinedicarboxylic acid (DPA) a biomarker of *Bacillus anthracis* restored the red fluorescence of Eu³⁺ at 593, 618, and 699 nm. This interaction produced a dual-emission ratiometric signal with a detection limit as low as 1.3 μM and strong anti-interference capabilities.

Moreover, recent insights into microbial signaling pathways further emphasize the importance of advanced detection tools. *Legionella pneumophila*, the causative agent of Legionnaires' disease, utilizes a quorum-sensing molecule known as *Legionella* autoinducer-1 (LAI-1) for

interspecies and interkingdom communication. Fan et al. demonstrated that LAI-1, synthesized by the enzyme LqsA, is secreted through outer membrane vesicles (OMVs), which facilitate both microbial signaling and host-pathogen interactions [146]. Using a *Vibrio cholerae* luminescence reporter and LC-MS/MS, LAI-1 was detected in OMVs derived from both *E. coli* and *L. pneumophila* expressing LqsA. These OMVs activated bacterial signaling pathways and inhibited amoeba migration, indicating their role in environmental virulence. Furthermore, overexpression of lqsA enhanced LAI-1 secretion, OMV production, and intracellular replication of *L. pneumophila* in macrophages. These findings underscore OMVs as vehicles for pathogen-derived biomolecules and advocate for the development of MOF-based nanozyme sensors targeting quorum-sensing signals for effective monitoring of waterborne microbial threats.

6.2. Soil and Air Microbial Sensing

MOF-based nanozymes have emerged as powerful tools for monitoring and modulating microbial activity in soil and air environments, owing to their unique features such as high surface area, tunable porosity, and intrinsic enzyme-mimicking properties. These materials play a critical role in environmental remediation, microbial detection, and pollutant degradation.

Su et al. demonstrated the application of Mn_3O_4 nanozyme-coated microbial consortia to remediate heavy metal-polluted paddy soils. By enhancing the microbial reduction of toxic Cr^{6+} and promoting the immobilization of As^{3+} , the nanozyme significantly reduced metal bioavailability, thereby lowering uptake by rice plants [147]. In the context of soil pesticide monitoring, Kumar et al. developed a nanozyme sensor array composed of carbon nanotubes decorated with various transition metals. This system could detect multiple pesticides in both soil and water samples with high sensitivity, showing detection limits in the range of 10.8–28.8 nM. The sensor array provided distinct colorimetric signatures for different analytes, allowing for easy field-level discrimination [148]. To mitigate cadmium (Cd) contamination in agricultural soils, Kong et al. introduced a microbial organic fertilizer (MOF) strategy. This approach boosted the population of iron-oxidizing bacteria in the rhizosphere, which facilitated iron plaque formation on rice roots. These plaques acted as a barrier to Cd uptake, effectively reducing Cd bioavailability in soil and its accumulation in rice grains [149].

For antibiotic residue detection, Ju et al. fabricated a Zn-based MOF sensor capable of selectively recognizing sulfasalazine, a common sulfonamide antibiotic. The sensor displayed a low detection limit of 31 nM and could be incorporated into paper-based test strips for on-site monitoring [150]. Additionally, Li et al. designed a cadmium-based MOF (Cd-MOF) capable of dual fluorescent detection of both antibiotics and

bacterial contaminants. This sensor achieved a limit of detection as low as 47 CFU/mL for *Streptomyces albus*, demonstrating its potential in environmental biosafety applications [151]. Addressing soil pollutants more broadly, Guselnikova et al. developed a MOF-5-based coating integrated with a plasmonic grating structure to serve as a highly sensitive surface-enhanced Raman scattering (SERS) platform. This device allowed for the trace-level detection of organophosphorus compounds, achieving detection limits down to 10^{-12} M, highlighting its utility in chemical hazard surveillance [152].

For airborne microbial threats, Zhu et al. engineered nanofibrous membranes by integrating UiO-66-NH₂ MOFs with quaternary ammonium groups. These membranes not only provided excellent filtration efficiency (>95%) against particulate matter but also exhibited potent antibacterial activity, making them suitable for high-performance air filters in healthcare and industrial settings [153]. Furthermore, Pan et al. reported a novel gas-phase biosensing platform based on cobalt-doped ZnO superparticles derived from MOFs. This material demonstrated high selectivity for detecting *Listeria monocytogenes* through its volatile biomarker, 3-hydroxy-2-butanone (3H-2B), offering a non-invasive and rapid detection method for foodborne pathogens in the air [154].

7. Challenges and Future Perspectives

MOF-based nanozyme microbial biosensors hold tremendous potential for highly sensitive and selective microbial detection. However, several critical challenges must be addressed before these systems can be widely adopted in practical applications [155].

First and foremost, the long-term stability and reusability of MOF nanozymes pose significant concerns. Many MOFs are prone to structural degradation and loss of catalytic activity after repeated usage or when exposed to harsh environmental conditions such as moisture, extreme pH levels, and microbial metabolites [156]. While innovative designs—like electrochemiluminescence biosensors incorporating covalently attached Ru complexes on NH₂-MIL-53(Al)—have demonstrated enhanced durability and consistent performance, these remain exceptional cases rather than the norm [157]. To improve the reliability of MOF nanozymes, future research should prioritize enhancing their structural robustness and catalytic longevity. Strategies such as ligand engineering, post-synthetic modifications, and forming composites with highly stable materials like graphene or polymers are promising approaches to achieve this goal.

In addition to stability challenges, achieving high selectivity and specificity for target microbial strains remains an unmet need. Most current MOF nanozyme biosensors rely largely on generalized catalytic activity, which limits their ability to precisely identify microbial strains within complex biological matrices [158]. To overcome this limitation, integrating MOFs with selective biorecognition elements such as

aptamers, antibodies, or molecularly imprinted polymers could significantly improve target specificity. Thanks to their tunable structures, large surface areas, and ease of surface modification, MOFs are ideally suited to develop sensors capable of highly selective microbial detection through mechanisms like photoinduced electron transfer (PET), resonance energy transfer (RET), and structural transformations [159].

Moreover, scaling up MOF production while maintaining quality and reducing costs remains a significant barrier to commercial viability. Although MOFs can be synthesized relatively straightforwardly in the laboratory, the transition to large-scale manufacturing is hindered by the need for high-purity metal precursors, energy-intensive synthesis, and complex purification processes. These factors not only increase production costs but also lead to batch-to-batch inconsistencies [160]. Therefore, future efforts should focus on developing green, low-cost, and scalable synthesis methods that ensure reproducibility and sustainability, making MOF nanozyme biosensors more economically feasible for widespread use.

Looking forward, the integration of MOF nanozymes into smart sensor platforms empowered by artificial intelligence (AI) and the Internet of Things (IoT) offers exciting prospects. Such integrated systems could facilitate real-time, remote monitoring of microbial contamination in diverse settings including food safety, water quality, and healthcare environments. However, creating seamless interfaces between MOF materials and electronic components, data processing units, and wireless communication modules presents considerable technical challenges that require interdisciplinary innovation [161]. The tunable catalytic properties of MOFs combined with smart responsive materials provide a strong foundation for developing next-generation adaptive biosensors with enhanced sensitivity and selectivity.

Finally, ensuring the biosafety of MOF nanozyme biosensors and navigating regulatory requirements are essential steps toward real-world implementation. The use of novel nanomaterials in clinical and environmental contexts demands comprehensive toxicity evaluations, biocompatibility assessments, and studies of environmental impact [162]. Potential cytotoxicity and long-term safety must be rigorously examined [163]. Establishing standardized testing protocols and clear regulatory guidelines will be critical to guarantee safe application and foster public trust [164]. Without addressing these concerns, the translation of MOF-based biosensors from laboratory prototypes to practical tools will remain limited.

Therefore, tackling challenges related to stability, specificity, scalability, smart integration, and safety is vital for unlocking the full potential of MOF-based nanozyme microbial biosensors. Through continued research and interdisciplinary innovation, these advanced biosensing platforms hold the promise to revolutionize microbial detection delivering sensitive, selective, cost-effective, and intelligent diagnostic solutions across a range of real-world applications.

8. Conclusions

Nanozymatic MOF-based biosensors have emerged as transformative platforms for highly sensitive and selective microbial detection, leveraging the intrinsic tunability of MOFs through structural alteration, composite formation, and precise control over pore size, surface functionality, and metal centers to finely tailor their enzyme-mimicking catalytic activity, stability, and specificity. These engineered nanozymes offer rapid, cost-effective, and robust biosensing solutions that outperform conventional enzyme-based sensors in stability, reusability, and responsiveness, making them ideal for diverse biomedical and environmental applications. Integration with advanced signal transduction systems and smart diagnostic devices further enhances their capacity for real-time, selective pathogen and microbial metabolite detection. This multifunctionality positions MOF nanozymes as next-generation intelligent biosensing materials critical for addressing challenges such as early disease diagnostics, antimicrobial resistance monitoring, and environmental pathogen surveillance. Looking ahead, efforts to improve biocompatibility, operational stability in complex biological and environmental matrices, and scalable synthesis methods will be essential to accelerate clinical translation and widespread deployment, bridging the gap between laboratory innovation and impactful real-world applications.

Author Contributions: Conceptualization, A.K. and S.C.; writing—original draft preparation, A.K.; writing—review and editing, A.K. and S.C.; visualization, A.K.; funding acquisition, S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Research Foundation of Korea (NRF-2023R1A2C1003669) and the Korea Environmental Industry & Technology Institute (KEITI) through “Technology Development Project for Biological Hazards Management in Indoor Air” Project, funded by the Korea Ministry of Environment (MOE) (G232021010381).

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

Abbreviations

MOF – metal–organic framework

ZIF-8 – zeolitic imidazolate framework-8

ZIF-L-Co – zeolitic imidazolate framework-L doped with cobalt and cysteine

TMB – 3,3',5,5'-tetramethylbenzidine

1329	H ₂ O ₂ – hydrogen peroxide
1330	LOx – lactate oxidase
1331	GOx – glucose oxidase
1332	OD – oxidase
1333	POD – peroxidase
1334	HRP – horseradish peroxidase
1335	SOD – superoxide dismutase
1336	CAT – catalase
1337	H – hemin
1338	GE – graphite electrode
1339	CFs – carbon microfibers
1340	CNTs – carbon nanotubes
1341	AuNPs – gold nanoparticles
1342	AgNPs – silver nanoparticles
1343	PtNPs – platinum nanoparticles
1344	PtMPs – platinum microparticles
1345	NPs – nanoparticles
1346	Au-TA – tannic acid-chelated gold nanoparticles
1347	Gr – graphene
1348	GDY/CNTs – graphdiyne/carbon nanotubes
1349	PAA – poly(acrylic acid)
1350	PDM – poly(N-2-dimethylaminoethyl methacrylate)
1351	bPEI-g-PEG – poly(ethylene imine)-graft-poly(ethylene glycol)
1352	DNA – deoxyribonucleic acid
1353	NANs – nucleic acid nanocapsules
1354	EGF – epidermal growth factor
1355	VBNC – viable but non-culturable
1356	DHBDC ²⁻ – 2,5-dihydroxyterephthalic acid
1357	DPA – 2,6-pyridinedicarboxylic acid
1358	OMVs – outer membrane vesicles
1359	LAI-1 – Legionella autoinducer-1
1360	MSRM – microbial sensitivity regulation mechanism
1361	SSZ – sulfasalazine

1362	OpdA – organophosphate degrading enzyme A
1363	ISF – interstitial fluid
1364	MNs – microneedles
1365	UA – uric acid
1366	ABTS – 2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid)
1367	AFB1 – aflatoxin B1
1368	Cys – cysteine
1369	ECL – electrochemiluminescence
1370	CL – chemiluminescence
1371	LOD – limit of detection
1372	LOQ – limit of quantification
1373	TVB-N – total volatile basic nitrogen
1374	TVC – total viable count
1375	FQs – fluoroquinolone antibiotics
1376	Cip – ciprofloxacin
1377	DAP – diaminophenazine
1378	PPi – pyrophosphate
1379	PPase – pyrophosphatase
1380	OPD – o-phenylenediamine
1381	S. aureus – Staphylococcus aureus
1382	MDRB – multidrug-resistant bacteria
1383	VP – Vibrio parahaemolyticus
1384	SapYZUs8 – bacteriophage
1385	H ₂ S – hydrogen sulfide
1386	NH ₃ – ammonia
1387	ROS – reactive oxygen species
1388	OECS – online electrochemical sensing system
1389	UiO-66 – University of Oslo-66 (zirconium-based MOF)
1390	UiO-66-NH ₂ – amino-functionalized University of Oslo-66 MOF
1391	
1392	
1393	
1394	
1395	
1396	

Reference

- [1] O. Oluwaseun, I. Singleton, A.S. Sant, Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID- 19 . The COVID-19 resource centre is hosted on Elsevier Connect , the company ' s public news and information, *Food Microbiol.* 73 (2020) 177–208.
- [2] J. Taylor, K. man Lai, M. Davies, D. Clifton, I. Ridley, P. Biddulph, Flood management: Prediction of microbial contamination in large-scale floods in urban environments, *Environ. Int.* 37 (2011) 1019–1029. <https://doi.org/10.1016/j.envint.2011.03.015>.
- [3] N.D. Novikova, Review of the knowledge of microbial contamination of the Russian manned spacecraft, *Microb. Ecol.* 47 (2004) 127–132. <https://doi.org/10.1007/s00248-003-1055-2>.
- [4] C.E. Edmiston, G.R. Seabrook, R.A. Cambria, K.R. Brown, B.D. Lewis, J.R. Sommers, C.J. Krepel, P.J. Wilson, S. Sinski, J.B. Towne, Molecular epidemiology of microbial contamination in the operating room environment: Is there a risk for infection?, *Surgery* 138 (2005) 573–582. <https://doi.org/10.1016/j.surg.2005.06.045>.
- [5] C. Dacarro, A.M. Picco, P. Grisoli, M. Rodolfi, Determination of aerial microbiological contamination in scholastic sports environments, *J. Appl. Microbiol.* 95 (2003) 904–912. <https://doi.org/10.1046/j.1365-2672.2003.02044.x>.
- [6] A. Tropea, Microbial Contamination and Public Health: An Overview, *Int. J. Environ. Res. Public Health* 19 (2022). <https://doi.org/10.3390/ijerph19127441>.
- [7] D.N. Fredricks, D.A. Relman, I. Diseases, Application of Polymerase Chain Reaction to the Diagnosis of Infectious Diseases Author (s): David N . Fredricks and David A . Relman Published by: Oxford University Press Stable URL : <http://www.jstor.org/stable/4460932> Application of Polymerase Chain, 29 (2018) 475–486.
- [8] L.G. Mendoza, P. McQuary, A. Mongan, R. Gangadharan, S. Brignac, M. Eggers, High-throughput microarray-based enzyme-linked immunosorbent assay (ELISA), *Biotechniques* 27 (1999) 778–788. <https://doi.org/10.2144/99274rr01>.
- [9] P. Austin, M. Elia, A systematic review and meta-analysis of the risk of microbial contamination of aseptically prepared doses in different environments, *J. Pharm. Pharm. Sci.* 12 (2009) 233–242. <https://doi.org/10.18433/j3jp4b>.
- [10] M.T. Koskinen, G.J. Wellenberg, O.C. Sampimon, J. Holopainen, A. Rothkamp, L. Salmikivi, W.A. van Haeringen, T.J.G.M. Lam, S. Pyörälä, Field comparison of real-time polymerase chain reaction and bacterial culture for identification of bovine mastitis bacteria, *J. Dairy Sci.* 93 (2010) 5707–5715. <https://doi.org/10.3168/jds.2010-3167>.
- [11] P.L. White, C. Parr, C. Thornton, R.A. Barnes, Evaluation of real-time PCR, galactomannan enzyme-linked immunosorbent assay (ELISA), and a novel lateral-flow device for diagnosis of invasive aspergillosis, *J. Clin. Microbiol.* 51 (2013) 1510–1516. <https://doi.org/10.1128/JCM.03189-12>.
- [12] L. Sutarlie, S.Y. Ow, X. Su, Nanomaterials-based biosensors for detection of microorganisms and microbial toxins, *Biotechnol. J.* 12 (2017) 1–26. <https://doi.org/10.1002/biot.201500459>.
- [13] R. Gupta, N. Raza, S.K. Bhardwaj, K. Vikrant, K.H. Kim, N. Bhardwaj, Advances in nanomaterial-based electrochemical biosensors for the detection of microbial toxins, pathogenic bacteria in food matrices, *J. Hazard. Mater.* 401 (2021) 123379. <https://doi.org/10.1016/j.jhazmat.2020.123379>.
- [14] J. Šefčovičová, J. Tkac, Application of nanomaterials in microbial-cell biosensor constructions, *Chem. Pap.* 69 (2015) 42–53. <https://doi.org/10.2478/s11696-014-0602-2>.

- [15] M.Q. Khan, J. Khan, M.A.H. Alvi, H. Nawaz, M. Fahad, M. Umar, Nanomaterial-based sensors for microbe detection: a review, *Discov. Nano* 19 (2024). <https://doi.org/10.1186/s11671-024-04065-x>.
- [16] N. Bhalla, Y. Pan, Z. Yang, A.F. Payam, Opportunities and Challenges for Biosensors and Nanoscale Analytical Tools for Pandemics: COVID-19, *ACS Nano* 14 (2020) 7783–7807. <https://doi.org/10.1021/acsnano.0c04421>.
- [17] Z. Li, X. Li, M. Jian, G.S. Geleta, Z. Wang, Two-dimensional layered nanomaterial-based electrochemical biosensors for detecting microbial toxins, *Toxins (Basel)* 12 (2019) 1–23. <https://doi.org/10.3390/toxins12010020>.
- [18] I. Bobrinetskiy, M. Radovic, F. Rizzotto, P. Vizzini, S. Jaric, Z. Pavlovic, V. Radonic, M.V. Nikolic, J. Vidic, Advances in nanomaterials-based electrochemical biosensors for foodborne pathogen detection, *Nanomaterials* 11 (2021) 1–26. <https://doi.org/10.3390/nano1102700>.
- [19] D. Mehta, D. Gupta, A. Kafle, S. Kaur, T.C. Nagaiah, Advances and Challenges in Nanomaterial-Based Electrochemical Immunosensors for Small Cell Lung Cancer Biomarker Neuron-Specific Enolase, *ACS Omega* 9 (2024) 33–51. <https://doi.org/10.1021/acsomega.3c06388>.
- [20] S.M. Khor, J. Choi, P. Won, S.H. Ko, Challenges and Strategies in Developing an Enzymatic Wearable Sweat Glucose Biosensor as a Practical Point-Of-Care Monitoring Tool for Type II Diabetes, *Nanomaterials* 12 (2022). <https://doi.org/10.3390/nano12020221>.
- [21] G. Bedendi, L.D. De Moura Torquato, S. Webb, C. Cadoux, A. Kulkarni, S. Sahin, P. Maroni, R.D. Milton, M. Grattieri, Enzymatic and Microbial Electrochemistry: Approaches and Methods, *ACS Meas. Sci. Au* 2 (2022) 517–541. <https://doi.org/10.1021/acsomega.2c00042>.
- [22] J.W. Lim, D. Ha, J. Lee, S.K. Lee, T. Kim, Review of micro/nanotechnologies for microbial biosensors, *Front. Bioeng. Biotechnol.* 3 (2015) 1–13. <https://doi.org/10.3389/fbioe.2015.00061>.
- [23] K. Chen, Z. Du, Y. Zhang, R. Bai, L. Zhu, W. Xu, Exploring Nucleic Acid Nanozymes: A New Frontier in Biosensor Development, *Biosensors* 15 (2025). <https://doi.org/10.3390/bios15030142>.
- [24] Y. An, X. Fang, J. Cheng, S. Yang, Z. Chen, Y. Tong, Research progress of metal-organic framework nanozymes in bacterial sensing, detection, and treatment, *RSC Med. Chem.* 15 (2023) 380–398. <https://doi.org/10.1039/d3md00581j>.
- [25] X. Niu, X. Li, Z. Lyu, J. Pan, S. Ding, X. Ruan, W. Zhu, D. Du, Y. Lin, Metal-organic framework based nanozymes: promising materials for biochemical analysis, *Chem. Commun.* 56 (2020) 11338–11353. <https://doi.org/10.1039/d0cc04890a>.
- [26] M.E. Mahmoud, M.F. Amira, S.M. Seleim, A.K. Mohamed, Amino-decorated magnetic metal-organic framework as a potential novel platform for selective removal of chromium (VI), cadmium (II) and lead (II), *J. Hazard. Mater.* 381 (2020) 120979. <https://doi.org/10.1016/j.jhazmat.2019.120979>.
- [27] M. Li, G. Zhang, A. Boakye, H. Chai, L. Qu, X. Zhang, Recent Advances in Metal-Organic Framework-Based Electrochemical Biosensing Applications, *Front. Bioeng. Biotechnol.* 9 (2021) 1–8. <https://doi.org/10.3389/fbioe.2021.797067>.
- [28] H.S. Wang, Y.H. Wang, Y. Ding, Development of biological metal-organic frameworks designed for biomedical applications: From bio-sensing/bio-imaging to disease treatment, *Nanoscale Adv.* 2 (2020) 3788–3797. <https://doi.org/10.1039/d0na00557f>.
- [29] S.E. Miller, M.H. Teplensky, P.Z. Moghadam, D. Fairen-Jimenez, Metal-organic frameworks as biosensors for luminescence-based detection and imaging, *Interface Focus* 6 (2016). <https://doi.org/10.1098/rsfs.2016.0027>.
- [30] X. Wang, P.C. Lan, S. Ma, Metal-Organic Frameworks for Enzyme Immobilization: Beyond Host Matrix Materials, *ACS Cent. Sci.* 6 (2020) 1497–1506. <https://doi.org/10.1021/acscentsci.0c00687>.
- [31] C. Zhang, X. Wang, M. Hou, X. Li, X. Wu, J. Ge, Immobilization on Metal-Organic Framework Engenders High Sensitivity for Enzymatic Electrochemical Detection, *ACS Appl. Mater. Interfaces* 9 (2017) 13831–13836. <https://doi.org/10.1021/acsami.7b02803>.

- [32] V. Aggarwal, S. Solanki, B.D. Malhotra, Applications of metal-organic framework-based bioelectrodes, *Chem. Sci.* **13** (2022) 8727–8743. <https://doi.org/10.1039/d2sc03441g>.
- [33] Y. Shang, G. Xing, H. Lin, S. Chen, T. Xie, J.M. Lin, Portable Biosensor with Bimetallic Metal-Organic Frameworks for Visual Detection and Elimination of Bacteria, *Anal. Chem.* **95** (2023) 13368–13375. <https://doi.org/10.1021/acs.analchem.3c02841>.
- [34] A. Elgazar, R. Sabouni, M. Ghommam, A.F. Majdalawieh, Novel metal-organic framework biosensing platform for detection of COVID-19 RNA, *Sci. Rep.* **14** (2024) 1–12. <https://doi.org/10.1038/s41598-024-75668-8>.
- [35] T. Leelasree, V. Selamneni, T. Akshaya, P. Sahatiya, H. Aggarwal, MOF based flexible, low-cost chemiresistive device as a respiration sensor for sleep apnea diagnosis, *J. Mater. Chem. B* **8** (2020) 10182–10189. <https://doi.org/10.1039/d0tb01748e>.
- [36] T. Zhang, M. Tang, S.Y. Yang, H. Fa, Y. Wang, D. Huo, C. Hou, M. Yang, Development of a novel ternary MOF nanozyme-based smartphone-integrated colorimetric and microfluidic paper-based analytical device for trace glyphosate detection, *Food Chem.* **464** (2025) 141780. <https://doi.org/10.1016/j.foodchem.2024.141780>.
- [37] Z. Zhang, Y. Li, Z. Yuan, L. Wu, J. Ma, W. Tan, Y. Sun, G. Zhang, H. Chai, MOF nanozymes: active sites and sensing applications, *Inorg. Chem. Front.* (2024) 400–429. <https://doi.org/10.1039/d4qi02555e>.
- [38] D. Wang, D. Jana, Y. Zhao, Metal-Organic Framework Derived Nanozymes in Biomedicine, *Acc. Chem. Res.* **53** (2020) 1389–1400. <https://doi.org/10.1021/acs.accounts.0c00268>.
- [39] J. Liang, Z. Liang, R. Zou, Y. Zhao, Heterogeneous Catalysis in Zeolites, Mesoporous Silica, and Metal-Organic Frameworks, *Adv. Mater.* **29** (2017) 1–21. <https://doi.org/10.1002/adma.201701139>.
- [40] T. Zorlu, D. Hetey, M.R. Reithofer, J.M. Chin, Physicochemical Methods for the Structuring and Assembly of MOF Crystals, *Acc. Chem. Res.* **57** (2024) 2105–2116. <https://doi.org/10.1021/acs.accounts.4c00250>.
- [41] L.R. Redfern, O.K. Farha, Mechanical properties of metal-organic frameworks, *Chem. Sci.* **10** (2019) 10666–10679. <https://doi.org/10.1039/c9sc04249k>.
- [42] V. Stavila, A.A. Talin, M.D. Allendorf, MOF-based electronic and opto-electronic devices, *Chem. Soc. Rev.* **43** (2014) 5994–6010. <https://doi.org/10.1039/c4cs00096j>.
- [43] N.C. Burtch, J. Heinen, T.D. Bennett, D. Dubbeldam, M.D. Allendorf, Mechanical Properties in Metal-Organic Frameworks: Emerging Opportunities and Challenges for Device Functionality and Technological Applications, *Adv. Mater.* **30** (2018) 1–18. <https://doi.org/10.1002/adma.201704124>.
- [44] A. Kidanemariam, S. Cho, Recent Advances in the Application of Metal-Organic Frameworks and Coordination Polymers in Electrochemical Biosensors, *Chemosensors* **12** (2024). <https://doi.org/10.3390/chemosensors12070135>.
- [45] G. Gharib, İ. Bütün, Z. Muganlı, G. Kozalak, İ. Namlı, S.S. Sarraf, V.E. Ahmadi, E. Toyran, A.J. van Wijnen, A. Koşar, Biomedical Applications of Microfluidic Devices: A Review, *Biosensors* **12** (2022). <https://doi.org/10.3390/bios12111023>.
- [46] X. Liu, Y. Fang, X. Chen, W. Shi, X. Wang, Z. He, F. Wang, C. Li, Cascaded nanozyme-based high-throughput microfluidic device integrating with glucometer and smartphone for point-of-care pheochromocytoma diagnosis, *Biosens. Bioelectron.* **251** (2024) 116105. <https://doi.org/10.1016/j.bios.2024.116105>.
- [47] N. Zhu, C. Liu, R. Liu, X. Niu, D. Xiong, K. Wang, D. Yin, Z. Zhang, Biomimic Nanozymes with Tunable Peroxidase-like Activity Based on the Confinement Effect of Metal-Organic Frameworks (MOFs) for Biosensing, *Anal. Chem.* **94** (2022) 4821–4830. <https://doi.org/10.1021/acs.analchem.2c00058>.
- [48] Y. Huang, J. Ren, X. Qu, Nanozymes: Classification, Catalytic Mechanisms, Activity Regulation,

- and Applications, *Chem. Rev.* **119** (2019) 4357–4412. <https://doi.org/10.1021/acs.chemrev.8b00672>.
- [49] K.A. Abdullah, T.F. Tahir, A.F. Qader, R.A. Omer, K.A. Othman, Nanozymes: Classification and Analytical Applications – A Review, *J. Fluoresc.* (2024). <https://doi.org/10.1007/s10895-024-03930-3>.
- [50] L. Gao, J. Zhuang, L. Nie, J. Zhang, Y. Zhang, N. Gu, T. Wang, J. Feng, D. Yang, S. Perrett, X. Yan, Intrinsic peroxidase-like activity of ferromagnetic nanoparticles, *Nat. Nanotechnol.* **2** (2007) 577–583. <https://doi.org/10.1038/nnano.2007.260>.
- [51] C. Cui, Q. Wang, Q. Liu, X. Deng, T. Liu, D. Li, X. Zhang, Porphyrin-based porous organic framework: An efficient and stable peroxidase-mimicking nanozyme for detection of H₂O₂ and evaluation of antioxidant, *Sensors Actuators, B Chem.* **277** (2018) 86–94. <https://doi.org/10.1016/j.snb.2018.08.097>.
- [52] O. Smutok, T. Kavetsky, T. Prokopiv, R. Serkiz, O. Šauša, I. Novák, H. Švajdlenková, I. Maľko, M. Gonchar, E. Katz, Biosensor Based on Peroxidase-Mimetic Nanozyme and Lactate Oxidase for Accurate L-Lactate Analysis in Beverages, *Biosensors* **12** (2022). <https://doi.org/10.3390/bios12111042>.
- [53] H. Zou, H. Wang, B. Xu, L. Liang, L. Shen, Q. Lin, Regenerative cerium oxide nanozymes alleviate oxidative stress for efficient dry eye disease treatment, *Regen. Biomater.* **9** (2022). <https://doi.org/10.1093/rb/rbac070>.
- [54] S. Ali, S. Sikdar, S. Basak, M. Mondal, K. Mallick, M. Salman Haydar, S. Ghosh, M. Nath Roy, Assemble multi-enzyme mimic tandem Mn₃O₄@ g-C₃N₄ for augment ROS elimination and label free detection, *Chem. Eng. J.* **463** (2023) 142355. <https://doi.org/10.1016/j.cej.2023.142355>.
- [55] S.S. Nadar, V.K. Rathod, Magnetic-metal organic framework (magnetic-MOF): A novel platform for enzyme immobilization and nanozyme applications, *Int. J. Biol. Macromol.* **120** (2018) 2293–2302. <https://doi.org/10.1016/j.ijbiomac.2018.08.126>.
- [56] S. Li, Y. Zhang, Q. Wang, A. Lin, H. Wei, Nanozyme-Enabled Analytical Chemistry, *Anal. Chem.* **94** (2022) 312–323. <https://doi.org/10.1021/acs.analchem.1c04492>.
- [57] Y. Qiu, G. Tan, Y. Fang, S. Liu, Y. Zhou, A. Kumar, M. Trivedi, D. Liu, J. Liu, Biomedical applications of metal-organic framework (MOF)-based nano-enzymes, *New J. Chem.* **45** (2021) 20987–21000. <https://doi.org/10.1039/d1nj04045f>.
- [58] X. Zhang, G. Li, D. Wu, X. Li, N. Hu, J. Chen, G. Chen, Y. Wu, Recent progress in the design fabrication of metal-organic frameworks-based nanozymes and their applications to sensing and cancer therapy, *Biosens. Bioelectron.* **137** (2019) 178–198. <https://doi.org/10.1016/j.bios.2019.04.061>.
- [59] S. Li, Y. Hou, Q. Chen, X. Zhang, H. Cao, Y. Huang, Promoting Active Sites in MOF-Derived Homobimetallic Hollow Nanocages as a High-Performance Multifunctional Nanozyme Catalyst for Biosensing and Organic Pollutant Degradation, *ACS Appl. Mater. Interfaces* **12** (2020) 2581–2590. <https://doi.org/10.1021/acsami.9b20275>.
- [60] G. Ren, F. Dong, Z. Zhao, K. Li, Y. Lin, Structure Defect Tuning of Metal-Organic Frameworks as a Nanozyme Regulatory Strategy for Selective Online Electrochemical Analysis of Uric Acid, *ACS Appl. Mater. Interfaces* **13** (2021) 52987–52997. <https://doi.org/10.1021/acsami.1c17974>.
- [61] A. Baranwal, S.A. Polash, V.K. Aralappanavar, B.K. Behera, V. Bansal, R. Shukla, Recent Progress and Prospect of Metal-Organic Framework-Based Nanozymes in Biomedical Application, *Nanomaterials* **14** (2024). <https://doi.org/10.3390/nano14030244>.
- [62] S. Khan, W.C. Cho, A. Sepahvand, S. Haji Hosseinali, A. Hussain, M.M. Nejadi Babadaei, M. Sharifi, M. Falahati, L.A. Jaragh-Alhadad, T.L.M. ten Hagen, X. Li, Electrochemical aptasensor based on the engineered core-shell MOF nanostructures for the detection of tumor antigens, *J. Nanobiotechnology* **21** (2023) 1–22. <https://doi.org/10.1186/s12951-023-01884-5>.
- [63] P. Ling, S. Cheng, N. Chen, C. Qian, F. Gao, Nanozyme-Modified Metal-Organic Frameworks

- with Multienzymes Activity as Biomimetic Catalysts and Electrocatalytic Interfaces, *ACS Appl. Mater. Interfaces* 12 (2020) 17185–17192. <https://doi.org/10.1021/acsami.9b23147>.
- [64] T. Li, X. Wang, Y. Wang, Y. Zhang, S. Li, W. Liu, S. Liu, Y. Liu, H. Xing, K.I. Otake, S. Kitagawa, J. Wu, H. Dong, H. Wei, Microenvironmental modulation breaks intrinsic pH limitations of nanozymes to boost their activities, *Nat. Commun.* 15 (2024) 1–11. <https://doi.org/10.1038/s41467-024-55163-4>.
- [65] V. Singh, D.K. Singh, M. Yadav, S. Singh, V. Rathour, A. Tiwari, V. Ganesan, A Co and Fe bimetallic MOF with enhanced electrocatalytic oxygen evolution performance: exploring the electronic environment modifications upon Fe incorporation, *Energy Adv.* 3 (2024) 636–647. <https://doi.org/10.1039/d3ya00572k>.
- [66] P. Wu, F. Gong, X. Feng, Y. Xia, L. Xia, T. Kai, P. Ding, Multimetallic nanoparticles decorated metal-organic framework for boosting peroxidase-like catalytic activity and its application in point-of-care testing, *J. Nanobiotechnology* 21 (2023) 1–12. <https://doi.org/10.1186/s12951-023-01946-8>.
- [67] S. Muhammad, B. Yao, A. Zhou, Z. Huang, S. Khan, F. Wei, Z. Luo, T.T. Isimjan, X. Yang, Unveiling dynamic surface transformations: Mo-doped Fe-based MOFs as next-generation oxygen evolution catalysts, *Green Chem.* (2025) 5554–5566. <https://doi.org/10.1039/d5gc01263e>.
- [68] R. Mehek, N. Iqbal, T. Noor, M.Z.B. Amjad, G. Ali, K. Vignarooban, M.A. Khan, Metal-organic framework based electrode materials for lithium-ion batteries: a review, *RSC Adv.* 11 (2021) 29247–29266. <https://doi.org/10.1039/d1ra05073g>.
- [69] H. Shen, Y. Tang, H. Ma, Accelerated peroxidase-like activity of ultrathin amine-tagged bimetallic MOF-74 nanozyme for construction of versatile bioassays from small molecules to enzymes and bacteria, *Microchem. J.* 201 (2024) 110706. <https://doi.org/10.1016/j.microc.2024.110706>.
- [70] S. Chen, T. Li, D. Deng, Y. Ji, R. Li, Bifunctional Fe@PCN-222 nanozyme-based cascade reaction system: Application in ratiometric fluorescence and colorimetric dual-mode sensing of glucose, *Spectrochim. Acta - Part A Mol. Biomol. Spectrosc.* 279 (2022) 121427. <https://doi.org/10.1016/j.saa.2022.121427>.
- [71] S. Zheng, Y. Sun, H. Xue, P. Braunstein, W. Huang, H. Pang, Dual-ligand and hard-soft-acid-base strategies to optimize metal-organic framework nanocrystals for stable electrochemical cycling performance, *Natl. Sci. Rev.* 9 (2022). <https://doi.org/10.1093/nsr/nwab197>.
- [72] P. Mohammadzadeh Jahani, S. Tajik, Z. Dourandish, Electrochemical Sensor Based on Ce-MOF Modified Screen Printed Electrode for Metronidazole Determination, *Chem. Methodol.* 8 (2024) 123–132. <https://doi.org/10.48309/chemm.2024.431008.1750>.
- [73] S.S. Mohammed Ameen, A. Bedair, M. Hamed, F. R. Mansour, K.M. Omer, Recent Advances in Metal-Organic Frameworks as Oxidase Mimics: A Comprehensive Review on Rational Design and Modification for Enhanced Sensing Applications, *ACS Appl. Mater. Interfaces* (2024). <https://doi.org/10.1021/acsami.4c17397>.
- [74] M. Li, J. Chen, W. Wu, Y. Fang, S. Dong, Oxidase-like MOF-818 Nanozyme with High Specificity for Catalysis of Catechol Oxidation, *J. Am. Chem. Soc.* 142 (2020) 15569–15574. <https://doi.org/10.1021/jacs.0c07273>.
- [75] M.Q. Tolentino, A.K. Hartmann, D.T. Loe, J.L. Rouge, Controlled release of small molecules and proteins from DNA-surfactant stabilized metal organic frameworks, *J. Mater. Chem. B* 8 (2020) 5627–5635. <https://doi.org/10.1039/d0tb00767f>.
- [76] S. Shahrokhian, S. Ranjbar, Aptamer immobilization on amino-functionalized metal-organic frameworks: An ultrasensitive platform for the electrochemical diagnostic of: *Escherichia coli* O157:H7, *Analyst* 143 (2018) 3191–3201. <https://doi.org/10.1039/c8an00725j>.
- [77] C. Li, T. Hang, Y. Jin, Atomically Fe-anchored MOF-on-MOF nanozyme with differential signal amplification for ultrasensitive cathodic electrochemiluminescence immunoassay, *Exploration*

- 3 (2023). <https://doi.org/10.1002/EXP.20220151>.
- [78] N. Rohra, G. Gaikwad, P. Dandekar, R. Jain, Microfluidic Synthesis of a Bioactive Metal-Organic Framework for Glucose-Responsive Insulin Delivery, *ACS Appl. Mater. Interfaces* 14 (2022) 8251–8265. <https://doi.org/10.1021/acsami.1c22153>.
- [79] Z. Liu, Y. Liu, Metal-Organic Frameworks as Sensors of Biomolecules, *ACS Symp. Ser.* 1394 (2021) 1–31. <https://doi.org/10.1021/bk-2021-1394.ch001>.
- [80] K.A.S. Usman, J.W. Maina, S. Seyedin, M.T. Conato, L.M. Payawan, L.F. Dumée, J.M. Razal, Downsizing metal–organic frameworks by bottom-up and top-down methods, *NPG Asia Mater.* 12 (2020). <https://doi.org/10.1038/s41427-020-00240-5>.
- [81] R. Singh, M. Musameh, Y. Gao, B. Ozcelik, X. Mulet, C.M. Doherty, Stable MOF@enzyme composites for electrochemical biosensing devices, *J. Mater. Chem. C* 9 (2021) 7677–7688. <https://doi.org/10.1039/d1tc00407g>.
- [82] N. Nataraj, T.W. Chen, Z.W. Gan, S.M. Chen, M.R. Hatshan, M.A. Ali, Bifunctional 3D-MOF-based nanoprobe for electrochemical sensing and nanozyme enhanced with peroxidase mimicking for colorimetric detection of acetaminophen, *Mater. Today Chem.* 23 (2022) 100725. <https://doi.org/10.1016/j.mtchem.2021.100725>.
- [83] K. Wang, N. Li, J. Zhang, Z. Zhang, F. Dang, Size-selective QD@MOF core-shell nanocomposites for the highly sensitive monitoring of oxidase activities, *Biosens. Bioelectron.* 87 (2017) 339–344. <https://doi.org/10.1016/j.bios.2016.08.026>.
- [84] Y. Chen, Z. Yang, H. Hu, X. Zhou, F. You, C. Yao, F.J. Liu, P. Yu, D. Wu, J. Yao, R. Hu, X. Jiang, H. Yang, Advanced Metal–Organic Frameworks-Based Catalysts in Electrochemical Sensors, *Front. Chem.* 10 (2022) 1–15. <https://doi.org/10.3389/fchem.2022.881172>.
- [85] K. Jayaramulu, S. Mukherjee, D.M. Morales, D.P. Dubal, A.K. Nanjundan, A. Schneemann, J. Masa, S. Kment, W. Schuhmann, M. Otyepka, R. Zbořil, R.A. Fischer, Graphene-Based Metal-Organic Framework Hybrids for Applications in Catalysis, Environmental, and Energy Technologies, *Chem. Rev.* 122 (2022) 17241–17338. <https://doi.org/10.1021/acs.chemrev.2c00270>.
- [86] H. Chai, K. Yu, Y. Zhao, Z. Zhang, S. Wang, C. Huang, X. Zhang, G. Zhang, MOF-On-MOF Dual Enzyme-Mimic Nanozyme with Enhanced Cascade Catalysis for Colorimetric/Chemiluminescent Dual-Mode Aptasensing, *Anal. Chem.* 95 (2023) 10785–10794. <https://doi.org/10.1021/acs.analchem.3c01905>.
- [87] S. Ma, S. Xiao, Y. Hong, Y. Bao, Z. Xu, D. Chen, X. Huang, Coupling metal organic frameworks nanozyme with carbon nanotubes on the gradient porous hollow fiber membrane for nonenzymatic electrochemical H₂O₂ detection, *Anal. Chim. Acta* 1293 (2024) 342285. <https://doi.org/10.1016/j.aca.2024.342285>.
- [88] J. Zhao, W. Zhu, Y. Mao, G. Ling, P. Zhang, Enhanced enzyme-like DNAzyme@MOFs for non-enzymatic uric acid detection in interstitial fluid, *Chem. Eng. J.* 500 (2024) 156837. <https://doi.org/10.1016/j.cej.2024.156837>.
- [89] H. Guan, Y. Zhang, S. Liu, A novel enhanced electrochemical sensor based on the peroxidase-like activity of Fe₃O₄@Au/MOF for the detection of p-aminophenol, *J. Appl. Electrochem.* 52 (2022) 989–1002. <https://doi.org/10.1007/s10800-022-01684-z>.
- [90] M.A. Tajwar, L. Qi, Dual Stimulus-Responsive Enzyme@Metal-Organic Framework-Polymer Composites toward Enhanced Catalytic Performance for Visual Detection of Glucose, *ACS Appl. Bio Mater.* 7 (2024) 325–331. <https://doi.org/10.1021/acsabm.3c00918>.
- [91] I. Chandio, Y. Ai, L. Wu, Q. Liang, Recent progress in MOFs-based nanozymes for biosensing, *Nano Res.* 17 (2024) 39–64. <https://doi.org/10.1007/s12274-023-5770-3>.
- [92] Z. Wang, M. Li, H. Bu, D.S. Zia, P. Dai, J. Liu, Nanomaterials for molecular recognition: specific adsorption and regulation of nanozyme activities, *Mater. Chem. Front.* 7 (2023) 3625–3640. <https://doi.org/10.1039/d3qm00208j>.
- [93] T. Ma, K. Huang, N. Cheng, Recent Advances in Nanozyme-Mediated Strategies for Pathogen

- Detection and Control, *Int. J. Mol. Sci.* **24** (2023). <https://doi.org/10.3390/ijms241713342>.
- [94] H. Hou, L. Wang, Y. Gao, J. Ping, F. Zhao, Recent advances in metal-organic framework-based nanozymes and their enabled optical biosensors for food safety analysis, *TrAC - Trends Anal. Chem.* **173** (2024) 117602. <https://doi.org/10.1016/j.trac.2024.117602>.
- [95] Z. Teymouri, H. Shekarchizadeh, K. Karami, Innovative real-time monitoring of fish freshness via agar-based film embedded with Cu-MOF colorimetric indicators, *Chem. Eng. J.* **510** (2025) 161751. <https://doi.org/10.1016/j.cej.2025.161751>.
- [96] S. Wang, W. Deng, L. Yang, Y. Tan, Q. Xie, S. Yao, Copper-Based Metal-Organic Framework Nanoparticles with Peroxidase-Like Activity for Sensitive Colorimetric Detection of *Staphylococcus aureus*, *ACS Appl. Mater. Interfaces* **9** (2017) 24440–24445. <https://doi.org/10.1021/acsami.7b07307>.
- [97] M. Ren, Y. Zhang, L. Yu, L. Qu, Z. Li, L. Zhang, A Co-based MOF as nanozyme with enhanced oxidase-like activity for highly sensitive and selective colorimetric differentiation of aminophenol isomers, *Talanta* **255** (2023) 124219. <https://doi.org/10.1016/j.talanta.2022.124219>.
- [98] Y. Li, W. Zhou, Y. Gao, X. Li, L. Yuan, G. Zhu, X. Gu, Z. Yang, Nanozyme colourimetry based on temperate bacteriophage for rapid and sensitive detection of *Staphylococcus aureus* in food matrices, *Int. J. Food Microbiol.* **416** (2024) 110657. <https://doi.org/10.1016/j.ijfoodmicro.2024.110657>.
- [99] W. Wang, S. Xiao, M. Zeng, H. Xie, N. Gan, Dual-mode colorimetric-electrochemical biosensor for *Vibrio parahaemolyticus* detection based on CuO₂ nanodot-encapsulated metal-organic framework nanozymes, *Sensors Actuators B Chem.* **387** (2023) 133835. <https://doi.org/10.1016/j.snb.2023.133835>.
- [100] R. Li, G. Qian, H. Shen, S. Yu, Self-cascade MOF@MOF nanozyme for ultrasensitive and low-background detection of multidrug-resistant bacteria, *Microchem. J.* **209** (2025) 112695. <https://doi.org/10.1016/j.microc.2025.112695>.
- [101] M. Hao, W. Huang, B. Feng, M. Teng, C. Ding, H. Shen, S. Yu, L. Wang, Layered Double Hydroxide-Derived Two-Dimensional Bimetallic Metal-Organic Framework Nanozymes for Microorganism Identification, *ACS Appl. Nano Mater.* **6** (2023) 4610–4618. <https://doi.org/10.1021/acsanm.3c00077>.
- [102] M. Liu, Y. Wang, J. Xiao, Y. Liu, Y. Ren, X. Gao, Colorimetric immunoassay of furazolidone metabolites based on iron-copper bimetallic organic framework nanoenzyme, *Microchim. Acta* **191** (2024) 1–10. <https://doi.org/10.1007/s00604-024-06657-x>.
- [103] M.Z. Abedeen, L. Yadav, R. Gupta, Sensitive electrochemical determination of hydrogen peroxide in milk and water utilizing AgNPs@Sn MOF nanozyme, *Microchim. Acta* **192** (2025). <https://doi.org/10.1007/s00604-025-07030-2>.
- [104] S. Mansouri, Detection of pathogenic bacteria with nanozymes-based colorimetric biosensors: Advances, challenges and future prospects, *Microchem. J.* **205** (2024) 111392. <https://doi.org/10.1016/j.microc.2024.111392>.
- [105] S. Chen, Y. Xie, X. Guo, D. Sun, Self-supporting electrochemical sensors for monitoring of cell-released H₂O₂ based on metal nanoparticle/MOF nanozymes, *Microchem. J.* **181** (2022) 107715. <https://doi.org/10.1016/j.microc.2022.107715>.
- [106] F. Mo, S. Zhong, T. You, J. Lu, D. Sun, Aptamer and DNAzyme-Functionalized Cu-MOF Hybrid Nanozymes for the Monitoring and Management of Bacteria-Infected Wounds, *ACS Appl. Mater. Interfaces* (2023). <https://doi.org/10.1021/acsami.3c10682>.
- [107] S. Zhang, R. Zhou, Y. Yi, G. Zhu, Innovative homogeneous voltammetric sensing strategy for fluoroquinolone antibiotics based on Fe-MOF nanozyme and graphdiyne/carbon nanotubes composites, *Microchem. J.* **213** (2025) 113739. <https://doi.org/10.1016/j.microc.2025.113739>.
- [108] H. Gao, H. Yu, S. Yang, F. Chai, H. Wu, M. Tian, Ultrasensitive detection of H₂O₂ via electrochemical sensor by graphene synergized with MOF-on-MOF nanozymes, *Microchim.*

- Acta 191 (2024). <https://doi.org/10.1007/s00604-024-06541-8>.
- [109] G. Yasin, S. Ibrahim, S. Ajmal, S. Ibraheem, S. Ali, A.K. Nadda, G. Zhang, J. Kaur, T. Maiyalagan, R.K. Gupta, A. Kumar, Tailoring of electrocatalyst interactions at interfacial level to benchmark the oxygen reduction reaction, *Coord. Chem. Rev.* 469 (2022) 214669. <https://doi.org/10.1016/j.ccr.2022.214669>.
- [110] J.J. Wei, G.Q. Wang, J.Y. Zheng, H.Y. Yang, A.J. Wang, L.P. Mei, J.J. Feng, T.Y. Cheang, Z-scheme Cu₂MoS₄/CdS/In₂S₃ nanocages heterojunctions-based PEC aptasensor for ultrasensitive assay of fumonisin B1 via signal amplification with hollow PtPd–CoSnO₃ nanozyme, *Biosens. Bioelectron.* 230 (2023) 115293. <https://doi.org/10.1016/j.bios.2023.115293>.
- [111] J.J. Wei, H.B. Li, G.Q. Wang, J.Y. Zheng, A.J. Wang, L.P. Mei, T. Zhao, J.J. Feng, Novel Ultrasensitive Photoelectrochemical Cytosensor Based on Hollow CdIn₂S₄/In₂S₃Heterostructured Microspheres for HepG2 Cells Detection and Inhibitor Screening, *Anal. Chem.* 94 (2022) 12240–12247. <https://doi.org/10.1021/acs.analchem.2c02982>.
- [112] X. Li, H. Zhu, P. Liu, M. Wang, J. Pan, F. Qiu, L. Ni, X. Niu, Realizing selective detection with nanozymes: Strategies and trends, *TrAC - Trends Anal. Chem.* 143 (2021) 116379. <https://doi.org/10.1016/j.trac.2021.116379>.
- [113] A. Sradha S, G. Louis, P. Keerthana, A. and Varghese, Recent advances in electrochemical and optical sensing of the organophosphate chlorpyrifos: a review, *Crit. Rev. Toxicol.* 52 (2022) 431–448. <https://doi.org/10.1080/10408444.2022.2122770>.
- [114] Z. Yi, S. Xiao, X. Kang, F. Long, A. Zhu, Bifunctional MOF-Encapsulated Cobalt-Doped Carbon Dots Nanozyme-Powered Chemiluminescence/Fluorescence Dual-Mode Detection of Aflatoxin B1, *ACS Appl. Mater. Interfaces* 16 (2024) 16494–16504. <https://doi.org/10.1021/acsami.4c00560>.
- [115] G.K. Ali, K.M. Omer, Nanozyme and Stimulated Fluorescent Cu-Based Metal-Organic Frameworks (Cu-MOFs) Functionalized with Engineered Aptamers as a Molecular Recognition Element for Thrombin Detection in the Plasma of COVID-19 Patients, *ACS Omega* 7 (2022) 36804–36810. <https://doi.org/10.1021/acsomega.2c05232>.
- [116] N. Zhu, T. Deng, Y.N. Zuo, J. Sun, H. Liu, X.E. Zhao, S. Zhu, Ratiometric fluorescence assay for sulfide ions with fluorescent MOF-based nanozyme, *Spectrochim. Acta - Part A Mol. Biomol. Spectrosc.* 295 (2023) 122620. <https://doi.org/10.1016/j.saa.2023.122620>.
- [117] Z. Liu, F. Wang, J. Ren, X. Qu, A series of MOF/Ce-based nanozymes with dual enzyme-like activity disrupting biofilms and hindering recolonization of bacteria, *Biomaterials* 208 (2019) 21–31. <https://doi.org/10.1016/j.biomaterials.2019.04.007>.
- [118] Y. Chen, N. Wang, Y. Lv, C. Zhou, Q. Liang, X. Su, Construction of the fluorescence sensing platform with a bifunctional Cu@MOF nanozyme for determination of alkaline phosphatase and its inhibitor, *Talanta* 278 (2024) 126564. <https://doi.org/10.1016/j.talanta.2024.126564>.
- [119] L. Hou, Y. Huang, T. Lin, F. Ye, S. Zhao, A FRET ratiometric fluorescence biosensor for the selective determination of pyrophosphate ion and pyrophosphatase activity based on difunctional Cu-MOF nanozyme, *Biosens. Bioelectron.* X 10 (2022) 100101. <https://doi.org/10.1016/j.biosx.2021.100101>.
- [120] T. Ye, L. Bai, J. Yu, W. Shi, M. Yuan, J. Wang, H. Cao, L. Hao, X. Wu, F. Yin, F. Xu, Fluorescent nanozyme for the dual-mode detection of tetracycline: Aggregation-induced luminescence and boosting peroxidase-like activity, *Food Control* 171 (2025) 111109. <https://doi.org/10.1016/j.foodcont.2024.111109>.
- [121] J. Du, F. Shi, K. Wang, Q. Han, Y. Shi, W. Zhang, Y. Gao, B. Dong, L. Wang, L. Xu, Metal-organic framework-based biosensing platforms for diagnosis of bacteria-induced infectious diseases, *TrAC - Trends Anal. Chem.* 175 (2024) 117707. <https://doi.org/10.1016/j.trac.2024.117707>.
- [122] C.R. Quijia, A. Renata Carolina, H.-S. Gilmar, G.F. Regina Célia, A. Guilherme, M. and Chorilli, Metal-organic frameworks for diagnosis and therapy of infectious diseases, *Crit. Rev. Microbiol.* 48 (2022) 161–196. <https://doi.org/10.1080/1040841X.2021.1950120>.

- [123] E. Cesewski, B.N. Johnson, Electrochemical biosensors for pathogen detection, *Biosens. Bioelectron.* 159 (2020) 112214. <https://doi.org/10.1016/j.bios.2020.112214>.
- [124] W.C. Hu, X.P. Zhao, J. Wang, C. Wang, X.H. Xia, Recent progress in metal-organic frameworks-based biosensors for pathogen detection, *TrAC - Trends Anal. Chem.* 178 (2024) 117857. <https://doi.org/10.1016/j.trac.2024.117857>.
- [125] W. Gu, S. Miller, C.Y. Chiu, Clinical Metagenomic Next-Generation Sequencing for Pathogen Detection, *Annu. Rev. Pathol. Mech. Dis.* 14 (2019) 319–338. <https://doi.org/10.1146/annurev-pathmechdis-012418-012751>.
- [126] M. Wang, R. Li, S. Sheng, H. Yang, X. Tang, J. Wang, F. Wang, Q. Zhang, L. Bai, X. Chen, J. Gao, X. Ren, H. Liu, J. Su, MOF nanozyme mediated bacterial metabolic regulation to intervene MRSA antibiotic tolerance for enhanced antimicrobial efficacy, *Nano Today* 63 (2025) 102753. <https://doi.org/10.1016/j.nantod.2025.102753>.
- [127] X. Li, G. Li, Q. Pan, F. Xue, Z. Wang, C. Peng, Rapid and ultra-sensitive lateral flow assay for pathogens based on multivalent aptamer and magnetic nanozyme, *Biosens. Bioelectron.* 250 (2024) 116044. <https://doi.org/10.1016/j.bios.2024.116044>.
- [128] C. Liu, H. Yu, B. Zhang, S. Liu, C. guang Liu, F. Li, H. Song, Engineering whole-cell microbial biosensors: Design principles and applications in monitoring and treatment of heavy metals and organic pollutants, *Biotechnol. Adv.* 60 (2022) 108019. <https://doi.org/10.1016/j.biotechadv.2022.108019>.
- [129] L. Gao, J. Wen, Z. Huang, S. Sheng, F. Xu, G. Ma, H. Tan, pH Meter-Assisted Biosensor Based on Glucose Oxidase-Conjugated Magnetic Metal-Organic Framework for On-Site Evaluation of Bacterial Contamination, *ACS Appl. Mater. Interfaces* 15 (2023) 31224–31232. <https://doi.org/10.1021/acsami.3c04377>.
- [130] Z. Ren, X. Wang, B. Jia, X. Liu, Y. Qu, W. Li, M. Zhao, Y.Q. Li, Nanozyme-Energized SERS Sensor for Ultrasensitive Dual-Mode Bacterial Detection, *ACS Appl. Nano Mater.* (2025). <https://doi.org/10.1021/acsanm.5c01030>.
- [131] H. Fu, H. Li, Q. He, G. Du, J. Li, Y. Zhang, Y. Liang, B. Lin, Flexible fiber composite functional materials based on Fe-MOFs nanozyme catalytic activity for efficient point-of-use water disinfection, *Chem. Eng. J.* 490 (2024) 151879. <https://doi.org/10.1016/j.cej.2024.151879>.
- [132] Q. Feng, C. Wang, X. Miao, M. Wu, A novel paper-based electrochemiluminescence biosensor for non-destructive detection of pathogenic bacteria in real samples, *Talanta* 267 (2024) 125224. <https://doi.org/10.1016/j.talanta.2023.125224>.
- [133] M. Falcone, B. De Angelis, F. Pea, A. Scalise, S. Stefani, R. Tasinato, O. Zanetti, L. Dalla Paola, Challenges in the management of chronic wound infections, *J. Glob. Antimicrob. Resist.* 26 (2021) 140–147. <https://doi.org/10.1016/j.jgar.2021.05.010>.
- [134] Y.F. Liu, P.W. Ni, Y. Huang, T. Xie, Therapeutic strategies for chronic wound infection, *Chinese J. Traumatol. - English Ed.* 25 (2022) 11–16. <https://doi.org/10.1016/j.cjtee.2021.07.004>.
- [135] L. Zhang, M. Ouyang, Y. Zhang, L. Zhang, Z. Huang, L. He, Y. Lei, Z. Zou, F. Feng, R. Yang, The fluorescence imaging and precise suppression of bacterial infections in chronic wounds by porphyrin-based metal-organic framework nanorods, *J. Mater. Chem. B* 9 (2021) 8048–8055. <https://doi.org/10.1039/d1tb01649k>.
- [136] X. Zhao, L. Chang, Y. Hu, S. Xu, Z. Liang, X. Ren, X. Mei, Z. Chen, Preparation of Photocatalytic and Antibacterial MOF Nanozyme Used for Infected Diabetic Wound Healing, *ACS Appl. Mater. Interfaces* 14 (2022) 18194–18208. <https://doi.org/10.1021/acsami.2c03001>.
- [137] X. Ren, L. Chang, Y. Hu, X. Zhao, S. Xu, Z. Liang, X. Mei, Z. Chen, Au@MOFs used as peroxidase-like catalytic nanozyme for bacterial infected wound healing through bacterial membranes disruption and protein leakage promotion, *Mater. Des.* 229 (2023) 111890. <https://doi.org/10.1016/j.matdes.2023.111890>.
- [138] D. Chao, Q. Dong, Z. Yu, D. Qi, M. Li, L. Xu, L. Liu, Y. Fang, S. Dong, Specific Nanodrug for

- Diabetic Chronic Wounds Based on Antioxidase-Mimicking MOF-818 Nanozymes, *J. Am. Chem. Soc.* **144** (2022) 23438–23447. <https://doi.org/10.1021/jacs.2c09663>.
- [139] C. Liu, X. Zhao, Z. Wang, Y. Zhao, R. Li, X. Chen, H. Chen, M. Wan, X. Wang, Metal-organic framework-modulated Fe₃O₄ composite au nanoparticles for antibacterial wound healing via synergistic peroxidase-like nanozymatic catalysis, *J. Nanobiotechnology* **21** (2023) 1–17. <https://doi.org/10.1186/s12951-023-02186-6>.
- [140] G. Le, Y. Li, L. Cai, L. Zhang, W. Pei, X. Zhu, S. Xu, J. Zhang, J. Chen, Lysozyme-based nanozyme encapsulated in double-network hydrogel for monitoring and repair of MRSA infected wounds, *Chem. Eng. J.* **477** (2023) 146421. <https://doi.org/10.1016/j.cej.2023.146421>.
- [141] W. Wu, Y. Yan, M. Xie, Y. Liu, L. Deng, H. Wang, A critical review on metal organic frameworks (MOFs)-based sensors for foodborne pathogenic bacteria detection, *Talanta* **281** (2025) 126918. <https://doi.org/10.1016/j.talanta.2024.126918>.
- [142] Y.L. Oon, Y.S. Oon, M. Ayaz, M. Deng, L. Li, K. Song, Waterborne pathogens detection technologies: advances, challenges, and future perspectives, *Front. Microbiol.* **14** (2023). <https://doi.org/10.3389/fmicb.2023.1286923>.
- [143] Q. Zhou, B. Natarajan, P. Kannan, Nanostructured biosensing platforms for the detection of food- and water-borne pathogenic *Escherichia coli*, *Anal. Bioanal. Chem.* **415** (2023) 3111–3129. <https://doi.org/10.1007/s00216-023-04731-6>.
- [144] H.S. Magar, B.A. Hemdan, H.R.M. Rashdan, R.Y.A. Hassan, Rapid and Selective Detection of Foodborne Pathogens Using a Disposable Bio-sensing System Designed by Stepwise Antibody Immobilization on AuNPs@Cu-MOF Nanocomposite, *J. Anal. Test.* **8** (2024) 478–492. <https://doi.org/10.1007/s41664-024-00319-w>.
- [145] X.Y. Zhao, J. Wang, H.G. Hao, H. Yang, Q.S. Yang, W.Y. Zhao, A water-stable europium-MOF sensor for the selective, sensitive ratiometric fluorescence detection of anthrax biomarker, *Microchem. J.* **166** (2021) 106253. <https://doi.org/10.1016/j.microc.2021.106253>.
- [146] M. Fan, P. Kiefer, P. Charki, C. Hedberg, J. Seibel, J.A. Vorholt, H. Hilbi, The *Legionella* autoinducer LAI-1 is delivered by outer membrane vesicles to promote interbacterial and interkingdom signaling, *J. Biol. Chem.* **299** (2023) 105376. <https://doi.org/10.1016/j.jbc.2023.105376>.
- [147] H.F. Su, Y.Z. Zhang, Z.C. Lu, Q.Y. Wang, A mechanism of microbial sensitivity regulation on interventional remediation by nanozyme manganese oxide in soil heavy metal pollution, *J. Clean. Prod.* **373** (2022) 133825. <https://doi.org/10.1016/j.jclepro.2022.133825>.
- [148] M. Kumar, N. Kaur, N. Singh, Colorimetric Nanozyme Sensor Array Based on Metal Nanoparticle-Decorated CNTs for Quantification of Pesticides in Real Water and Soil Samples, *ACS Sustain. Chem. Eng.* **12** (2024) 728–736. <https://doi.org/10.1021/acssuschemeng.3c04153>.
- [149] F. Kong, S. Lu, Effects of microbial organic fertilizer (MOF) application on cadmium uptake of rice in acidic paddy soil: Regulation of the iron oxides driven by the soil microorganisms, *Environ. Pollut.* **307** (2022). <https://doi.org/10.1016/j.envpol.2022.119447>.
- [150] P. Ju, G. Zhang, W. Lu, S. Wang, A. Li, Q. Zhang, B. Li, S. Fei, L. Jiang, E. Zhang, A new hydroxyl group functionalized Zn-MOF as an efficient fluorescent probe for sulfasalazine residue detection in water, milk and soil, *J. Mol. Struct.* **1311** (2024) 138437. <https://doi.org/10.1016/j.molstruc.2024.138437>.
- [151] Q.Q. Li, M.J. Wen, Y. Sen Zhang, Z.S. Guo, X. Bai, J.X. Song, P. Liu, Y.Y. Wang, J.L. Li, Multiple fluorescence response behaviors towards antibiotics and bacteria based on a highly stable Cd-MOF, *J. Hazard. Mater.* **423** (2022) 127132. <https://doi.org/10.1016/j.jhazmat.2021.127132>.
- [152] O. Guselnikova, P. Postnikov, R. Elashnikov, E. Miliutina, V. Svorcik, O. Lyutakov, Metal-organic framework (MOF-5) coated SERS active gold gratings: A platform for the selective detection of organic contaminants in soil, *Anal. Chim. Acta* **1068** (2019) 70–79. <https://doi.org/10.1016/j.aca.2019.03.058>.

- [153] Z. Zhu, Y. Zhang, L. Bao, J. Chen, S. Duan, S.C. Chen, P. Xu, W.N. Wang, Self-decontaminating nanofibrous filters for efficient particulate matter removal and airborne bacteria inactivation, *Environ. Sci. Nano* 8 (2021) 1081–1095. <https://doi.org/10.1039/d0en01230k>.
- [154] M.M. Pan, D. Feng, Y. Ouyang, D. Yang, X. Yu, L. Xu, I. Willner, MOF-templated synthesis of cobalt-doped zinc oxide superparticles for detection of the 3-hydroxy-2-butanone microbial biomarker, *Sensors Actuators B Chem.* 358 (2022). <https://doi.org/10.1016/j.snb.2022.131482>.
- [155] J.E. d. S. Souza, G.P. d. Oliveira, J.Y.N.H. Alexandre, J.G.L. Neto, M.B. Sales, P.G. d. S. Junior, A.L.B. d. Oliveira, M.C.M. d. Souza, J.C.S. do. Santos, A Comprehensive Review on the Use of Metal–Organic Frameworks (MOFs) Coupled with Enzymes as Biosensors, *Electrochem* 3 (2022) 89–113. <https://doi.org/10.3390/electrochem3010006>.
- [156] A. Ali, M. Ovais, H. Zhou, Y. Rui, C. Chen, Tailoring metal-organic frameworks-based nanozymes for bacterial theranostics, *Biomaterials* 275 (2021) 120951. <https://doi.org/10.1016/j.biomaterials.2021.120951>.
- [157] L. Sun, Y. Chen, Y. Duan, F. Ma, Electrogenated Chemiluminescence Biosensor Based on Functionalized Two-Dimensional Metal–Organic Frameworks for Bacterial Detection and Antimicrobial Susceptibility Assays, *ACS Appl. Mater. Interfaces* 13 (2021) 38923–38930. <https://doi.org/10.1021/acsami.1c11949>.
- [158] J. Qin, N. Guo, J. Yang, J. Wei, Recent advances in metal oxide nanozyme-based optical biosensors for food safety assays, *Food Chem.* 447 (2024) 139019. <https://doi.org/10.1016/j.foodchem.2024.139019>.
- [159] Y. Zhao, H. Zeng, X.W. Zhu, W. Lu, D. Li, Metal-organic frameworks as photoluminescent biosensing platforms: Mechanisms and applications, *Chem. Soc. Rev.* 50 (2021) 4484–4513. <https://doi.org/10.1039/d0cs00955e>.
- [160] M.W.N. Leoi, X.T. Zheng, Y. Yu, J. Gao, D.H.S. Ong, C.Z.H. Koh, P. Chen, L. Yang, Redefining Metal Organic Frameworks in Biosensors: Where Are We Now?, *ACS Appl. Mater. Interfaces* (2025). <https://doi.org/10.1021/acsami.4c19307>.
- [161] Y. Zhang, C. Zhang, W. Qian, F. Lei, Z. Chen, X. Wu, Y. Lin, F. Wang, Recent advances in MOF-based nanozymes: Synthesis, activities, and bioapplications, *Biosens. Bioelectron.* 263 (2024) 116593. <https://doi.org/10.1016/j.bios.2024.116593>.
- [162] Z. Xu, L. li Long, Y. qiu Chen, M.L. Chen, Y.H. Cheng, A nanozyme-linked immunosorbent assay based on metal–organic frameworks (MOFs) for sensitive detection of aflatoxin B1, *Food Chem.* 338 (2021) 128039. <https://doi.org/10.1016/j.foodchem.2020.128039>.
- [163] S. Ahmadi, K. Rahimizadeh, A. Shafiee, N. Rabiee, S. Iravani, Nanozymes and their emerging applications in biomedicine, *Process Biochem.* 131 (2023) 154–174. <https://doi.org/10.1016/j.procbio.2023.06.014>.
- [164] L. Feng, M. Zhang, Z. Fan, Current trends in colorimetric biosensors using nanozymes for detecting biotoxins (bacterial food toxins, mycotoxins, and marine toxins), *Anal. Methods* (2024) 6771–6792. <https://doi.org/10.1039/d4ay01184h>.