CHAPTER 11

Water-stable metal-organic frameworks-based materials as optical sensors

Khasan Berdimuradov[1], Yusufboy Rajabov[2], Jaykhun Mamatov[2], Elyor Berdimurodov[2,3,4], Ashish Kumar[5], and Anvar Khamidov[6]

[1]Shahrisabz Faculty of Food Engineering, Karshi State Technical University, Karshi, Kashkadaryo, Uzbekistan
[2]Faculty of Chemistry, National University of Uzbekistan, Tashkent, Uzbekistan
[3]Department of Physical Chemistry, National University of Uzbekistan, Tashkent, Uzbekistan
[4]University of Tashkent for Applied Sciences, Tashkent, Uzbekistan
[5]Department of Science, Technology and Technical Education, Nalanda College of Engineering, Bihar Engineering University, Government of Bihar, Bihar Sharif, Bihar, India
[6]School of Energy Materials, Mahatma Gandhi University, Kottayam, Kerala, India

Contents

11.1 Introduction 263
11.2 Water-stable metal-organic frameworks-based materials in optical sensors 266
11.2.1 Classification 266
11.3 Carbon-based metal-organic framework composites in optical sensors 267
11.4 Metal/metal-organic framework composites in optical sensors 270
11.5 Lanthanide-based metal-organic framework composites in optical sensors 273
11.6 Future suggestions 276
11.7 Conclusion 277
References 277

11.1 Introduction

Metal-organic frameworks (MOFs) have emerged over the past two decades as one of the most versatile classes of porous crystalline materials, combining inorganic metal nodes with organic linkers to form extended, tunable architectures (Adeel et al., 2021; Du et al., 2021; Hoppe et al., 2018; Rezvani Jalal et al., 2020). Their high surface area, well-defined pore structures, and chemically adjustable frameworks have enabled a range of applications, from gas storage and catalysis to drug delivery and chemical sensing (Chen et al., 2019; Li et al., 2018; Xiao et al., 2022; Zheng et al., 2018). Among these, the development of MOFs for optical sensing has

Water-Stable Metal-Organic Frameworks (WSMOFs)
DOI: https://doi.org/10.1016/B978-0-443-29256-9.00010-9
© 2026 Elsevier Inc. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

garnered significant attention. Optical sensors based on MOFs rely on changes in luminescence intensity, wavelength shifts, or fluorescence lifetimes in response to analyte binding, enabling rapid, sensitive, and often selective detection (Baghayeri et al., 2020; Mousavi et al., 2020; Zheng et al., 2020). Despite the obvious appeal of employing MOFs as optical sensors, one critical limitation has traditionally hindered their practical deployment: instability in aqueous environments.

Water-induced degradation of MOFs can occur through several pathways, including ligand hydrolysis, metal-oxo cluster breakdown, and structural collapse induced by solvent exchange (Liu et al., 2020; Olorunyomi et al., 2022). Early-generation MOFs, such as many zinc-based systems, are highly susceptible to water, thereby restricting their use in real-world, water-rich environments (Wang et al., 2022). Since a significant proportion of sensing applications—including environmental pollutant detection, biochemical assays, and biomedical diagnostics—necessitates stable operation in aqueous media, the quest for water-stable MOFs has emerged as a crucial frontier in the field (Anik et al., 2019). Over the last decade, researchers have focused on designing robust, water-stable MOFs that can withstand harsh conditions while maintaining their structural integrity and optical responsiveness.

A variety of strategies have been developed to enhance the water stability of MOFs. From a metal-node perspective, employing high-valent cations such as Zr(IV), Al(III), Cr(III), and Fe(III) can yield ultra-stable frameworks like UiO-66 (Zr-based), MIL-53, MIL-101 (Cr-based), and others with remarkable resistance to water and even acidic or basic conditions (Jalili et al., 2019; Yan et al., 2022; Zhang et al., 2023). Meanwhile, judicious ligand selection—incorporating hydrophobic linkers, sterically protected coordination sites, or strongly coordinating functional groups—further improves framework resilience (Li, 2021). Postsynthetic modifications, including the introduction of hydrophobic coatings, doping with stable secondary building units, and covalent binding of protective groups, have also proven effective in mitigating hydrolytic degradation (Qian, 2020; Sheta et al., 2019; Xu et al., 2019). Collectively, these methods have ushered in a new era of MOFs that retain their crystallinity, porosity, and luminescence even after prolonged exposure to water.

Concomitant with improvements in stability, a nuanced understanding of the optical response mechanisms in water-stable MOFs has also evolved. The luminescent properties of MOFs arise from a combination of factors: the intrinsic fluorescence of organic linkers, ligand-to-metal charge transfer

states, guest-induced quenching or enhancement, and energy transfer dynamics between the host framework and guest molecules (Du et al., 2020; Gutiérrez et al., 2020). By tailoring pore size, shape, and functional groups, it is possible to control how analyte molecules interact with luminescent centers. For instance, some MOFs exhibit high selectivity and sensitivity toward heavy metals (e.g., Hg(II), Pb(II)) or anions (e.g., F^-, CN^-) due to specific host-guest chemistries (Bodkhe et al., 2023; Dong et al., 2020; Surya et al., 2019). Others target volatile organic compounds (VOCs), explosives, or biomolecules, capitalizing on the confined space and specific chemical environments within the MOF pores (Nie et al., 2021; Wei et al., 2019; Yang et al., 2021). Achieving robust performance in aqueous conditions can substantially broaden the spectrum of practical applications, ranging from environmental monitoring of pollutants in wastewater to biomedical diagnostics and in vivo imaging (Fig. 11.1).

This chapter focuses on the emerging field of water-stable MOF-based materials as optical sensors. We begin by reviewing the design principles that underpin the creation of water-stable frameworks, including metal choice, ligand functionalization, and postsynthetic modifications. We then delve into the fundamental photophysical mechanisms that enable these materials to serve as highly responsive optical sensors. Representative examples of zirconium, aluminum, and other metal-based MOFs are presented, highlighting their utility in detecting heavy metal ions, anions, small organic molecules, and biological species under aqueous conditions. Finally, we consider recent advances in device integration, such as the

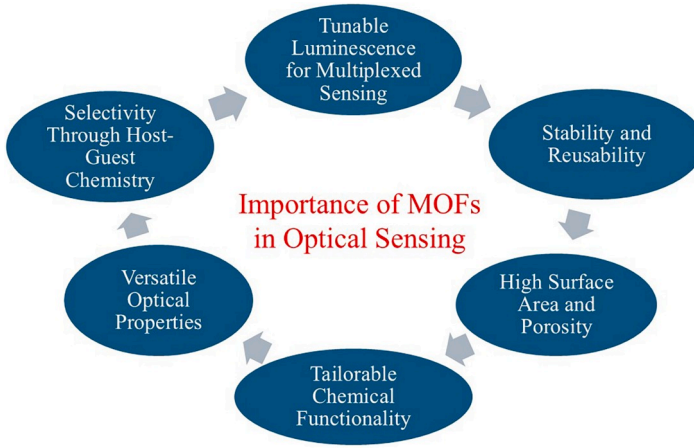


Figure 11.1 Importance of metal-organic frameworks (MOFs) in optical sensing.

fabrication of thin films, membranes, and composites for portable sensing platforms. These steps toward real-world implementation highlight the transformative potential of water-stable MOFs in bridging laboratory research and applied technologies.

By examining the interaction between stability, luminescence, and host-guest chemistry, this chapter aims to provide a comprehensive understanding of how water-stable MOFs can be engineered into versatile, sensitive, and selective optical sensors. With ongoing research continuing to push the boundaries of stability and functionality, the future of water-stable MOF-based optical sensing appears both robust and vibrant.

11.2 Water-stable metal-organic frameworks-based materials in optical sensors

11.2.1 Classification

MOFs have emerged as versatile materials in optical sensing due to their modular architecture and tunable properties. Among the various types of MOF-based materials, carbon-based MOF composites stand out for their enhanced conductivity, mechanical strength, and high surface area (Fig. 11.2). These composites, often integrated with graphene or carbon nanotubes (CNT), are widely used for sensing applications, including the detection of organic pollutants, gases, and biomolecules. Graphene/MOF composites influence the high electrical conductivity and robust mechanical properties of graphene, facilitating efficient electron transfer and

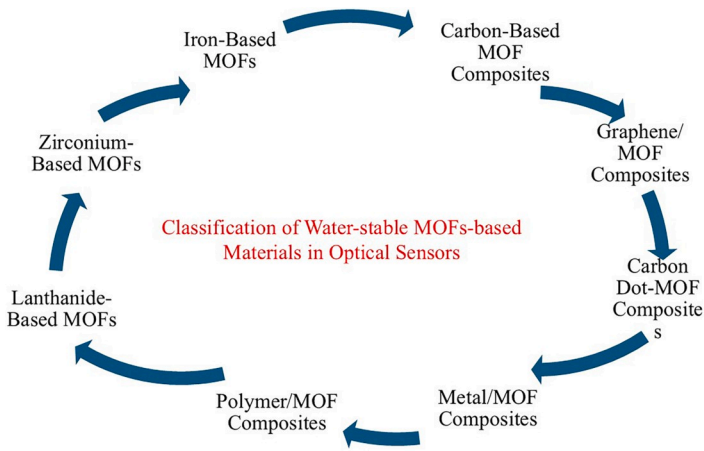


Figure 11.2 Classification of water-stable metal-organic framework (MOF)-based materials in optical sensors.

enabling the detection of VOCs, heavy metals, and other pollutants. Similarly, carbon dot-MOF composites are valued for their strong luminescent properties, which arise from efficient charge transfer between carbon dots (CDs) and MOF linkers, making them ideal for sensing biological markers and heavy metals.

Incorporating metal nanoparticles into MOFs forms metal/MOF composites, which enhance luminescence and selectivity due to the plasmonic and catalytic properties of the metal components. These materials are especially effective in fluorescence-based sensing applications. Another important category is polymer/MOF composites, which combine the flexibility and film-forming ability of polymers with the porous, functional nature of MOFs, enabling their use in thin-film sensors for real-time detection. Lanthanide-based MOFs, featuring intrinsic photoluminescent properties from lanthanide metal centers, are particularly suited for detecting explosives, toxic ions, and complex organic compounds due to their sharp emission peaks and long luminescence lifetimes.

Zirconium-based MOFs, known for their exceptional water stability and chemical resilience, are used for detecting anions, organic molecules, and other analytes in challenging environments. Similarly, iron-based MOFs offer strong metal-oxo bonding and chemical stability, making them effective for sensing reactive oxygen species and other high-reactivity analytes. The diverse chemical and structural characteristics of these MOF-based materials allow them to be tailored for specific optical sensing applications, providing highly sensitive, selective, and durable solutions across environmental, biomedical, and industrial fields.

11.3 Carbon-based metal-organic framework composites in optical sensors

Carbon-based MOF composites have emerged as a promising category of materials in optical sensing due to their synergistic properties. These composites combine the high porosity, tunable functionality, and host-guest chemistry of MOFs with the exceptional electrical conductivity, mechanical strength, and optical properties of carbon-based materials such as graphene, CNTs, and CDs (Adeel et al., 2021; Hoppe et al., 2018; Rezvani Jalal et al., 2020). The integration of carbon materials enhances the electronic communication within the composite, making them highly efficient for optical sensing applications (Du et al., 2021; Xiao et al., 2022). Graphene/MOF composites, in particular, leverage graphene's excellent

conductivity and π–π stacking interactions with MOF frameworks, enabling efficient charge transfer mechanisms. These composites have been widely used in the detection of gases, metal ions, and organic molecules (Chen et al., 2019; Li et al., 2018; Zheng et al., 2018). For example, the incorporation of graphene enhances the fluorescence response of MOFs by acting as a conductive bridge, facilitating energy or electron transfer processes between the analyte and the MOF's active sites. Similarly, CNT/MOF composites exhibit superior structural robustness and facilitate signal transduction, making them suitable for detecting pollutants, VOCs, and biomolecules (Baghayeri et al., 2020; Zheng et al., 2020). The CNTs provide a large surface area and high conductivity, which complement the MOF's selective adsorption properties.

Carbon dot-MOF composites are another notable example, where CDs contribute strong luminescence and high quantum yields. The optical properties of these composites arise from the interaction between the CDs and the MOF linkers, leading to enhanced fluorescence or ratiometric sensing capabilities. These materials have shown excellent performance in detecting heavy metals, small organic molecules, and biological markers due to their high sensitivity and selectivity (Liu et al., 2020; Mousavi et al., 2020; Olorunyomi et al., 2022). The synergy in carbon-based MOF composites lies in their ability to amplify optical signals while maintaining structural stability. Carbon materials prevent the agglomeration of MOF particles, enhance the durability of the composite, and enable the formation of hybrid structures with improved sensing performance. Furthermore, the combination of MOFs with carbon materials facilitates the fabrication of advanced sensing platforms, such as thin films, membranes, and flexible devices, that are suitable for portable or in-field applications (Anik et al., 2019; Wang et al., 2022; Zhang et al., 2023). Overall, carbon-based MOF composites bridge the gap between high-performance sensing materials and practical implementation. Their multifunctional properties and ease of integration into device architectures make them an indispensable component of next-generation optical sensors, particularly in environmental monitoring, biomedical diagnostics, and industrial safety applications. Future developments in this area are expected to focus on optimizing the interface between MOFs and carbon materials to further enhance sensing efficiency and selectivity (Jalili et al., 2019; Li, 2021; Yan et al., 2022).

Fig. 11.3 illustrates the synthetic procedure for creating CDs embedded metal-organic framework@molecularly imprinted polymer

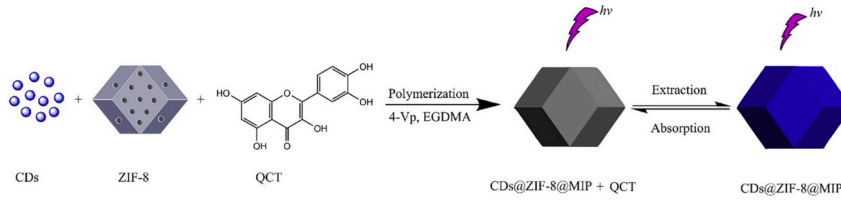


Figure 11.3 Preparation of CDs@ZIF-8@MIP and its application in QCT sensing. From Xu, L., Pan, M., Fang, G., & Wang, S. (2019). Carbon dots embedded metal-organic framework@molecularly imprinted nanoparticles for highly sensitive and selective detection of quercetin. Sensors and Actuators B: Chemical, 286, 321–327. https://doi.org/10.1016/j.snb.2019.01.156.

(CDs@ZIF-8@MIP) nanoparticles designed for the selective and sensitive detection of quercetin (QCT) (Xu et al., 2019). The synthesis begins with the preparation of ZIF-8, a zeolitic imidazolate framework known for its high surface area, stability, and large pores. Luminescent CDs are then incorporated into the ZIF-8 structure. This step enhances the optical signal transduction capabilities by embedding a luminescent material within the porous MOF matrix. A molecular imprinting polymerization process is subsequently conducted, during which QCT molecules act as templates. Functional monomers and cross-linkers form a polymer shell around the ZIF-8/CD composite, creating specific binding sites for QCT within the MIP layer. This method integrates the benefits of molecular imprinting, luminescent CDs, and MOF properties to produce a highly selective and sensitive fluorescent sensor. Fig. 11.4 presents the UV–Vis absorption spectra and fluorescence (FL) characteristics of QCT and the CDs@ZIF-8@MIP sensor. The spectra highlight the interaction between QCT and the CDs@ZIF-8@MIP. Before interaction, the absorption spectrum of CDs@ZIF-8@MIP demonstrates characteristic peaks of both ZIF-8 and CDs. After interaction with QCT, changes in the spectrum indicate effective adsorption and the establishment of host-guest interactions. The overlap between the excitation spectrum of CDs@ZIF-8@MIP and the absorption spectrum of QCT provides evidence of fluorescence quenching via the inner filter effect (IFE). The FL response of the sensor decreases linearly with increasing concentrations of QCT, showcasing its ability to transduce molecular recognition events into detectable fluorescence signals. This highlights the CDs@ZIF-8@MIP as a promising platform for optosensing applications, demonstrating a strong linear relationship and a low detection limit.

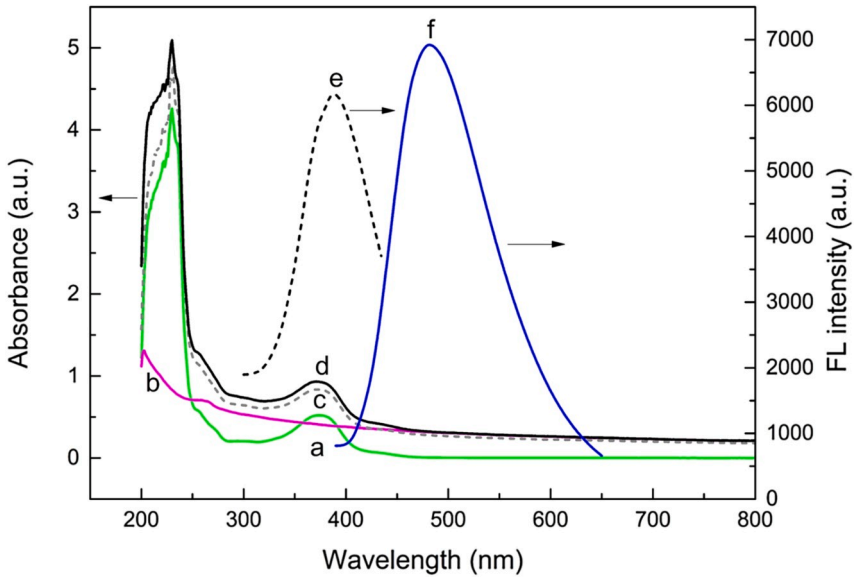


Figure 11.4 UV–vis absorption spectra of QCT (a), CDs@ZIF-8@MIP before (b) and after (c) interaction with QCT, and the stacked curve (d) of (a) and (b), FL excitation (e), and emission (f) spectra of the CDs@ZIF-8@MIP. From Xu, L., Pan, M., Fang, G., & Wang, S. (2019). Carbon dots embedded metal-organic framework@molecularly imprinted nanoparticles for highly sensitive and selective detection of quercetin. Sensors and Actuators B: Chemical, 286, 321–327. https://doi.org/10.1016/j.snb.2019.01.156.

11.4 Metal/metal-organic framework composites in optical sensors

Metal/MOF composites have emerged as a significant category in optical sensing due to their unique combination of properties from both metal nanoparticles and MOFs. The incorporation of metal nanoparticles, such as gold, silver, and copper, into MOFs enhances the luminescence, selectivity, and stability of the composite material (Gutiérrez et al., 2020; Qian, 2020; Sheta et al., 2019). MOFs provide a highly porous and organized framework that acts as a host for the metal nanoparticles, facilitating uniform distribution and preventing agglomeration. The metal nanoparticles contribute to enhanced optical properties through plasmonic effects and catalytic activity, making these composites highly effective in detecting a wide range of analytes, including gases, ions, and organic molecules (Bodkhe et al., 2023; Du et al., 2020; Surya et al., 2019).

The synergy between metal nanoparticles and MOFs significantly amplifies the optical signals in sensing applications. For example, gold nanoparticles embedded in MOFs can exhibit strong surface plasmon resonance (SPR), which enhances fluorescence or Raman scattering signals. This makes the composites particularly useful in applications requiring high sensitivity, such as trace-level detection of toxic chemicals or biomolecules. Additionally, silver nanoparticles embedded in MOFs have demonstrated remarkable fluorescence enhancement and quenching capabilities, enabling the detection of analytes like heavy metals and organic dyes with exceptional precision (Dong et al., 2020; Nie et al., 2021; Wei et al., 2019). Copper nanoparticles, on the other hand, provide unique catalytic and optical properties, making them suitable for detecting reactive oxygen species and environmental pollutants.

The versatility of metal/MOF composites extends to their adaptability in various sensing platforms. These composites can be engineered into thin films, membranes, or integrated into optical fibers, making them highly practical for portable and on-site detection systems. Furthermore, the robust interaction between the metal nanoparticles and the MOF framework ensures long-term stability, even under harsh conditions, such as high humidity or acidic environments (Xuan et al., 2019; Yang et al., 2021). The tunable properties of both components allow for the design of targeted sensors with high selectivity and sensitivity, addressing the needs of diverse fields, including environmental monitoring, biomedical diagnostics, and food safety. Future research is expected to focus on optimizing the integration process and exploring new metal/MOF combinations to further enhance sensing performance and broaden their application scope (Appelhans et al., 2021; Zhou et al., 2023).

Guselnikova et al. (2019) focus on the innovative use of MOF-5 films coated on Surface-Enhanced Raman Scattering (SERS)-active gold gratings for the selective and sensitive detection of organophosphorus pesticides, such as Paraoxon and Fenitrothion. The MOF-5 enhances the substrate's capability to adsorb these pesticides due to its porous structure and high affinity for organic molecules. The integration with gold gratings facilitates effective plasmonic excitation, enabling ultra-sensitive SERS detection. The detection limits achieved for the pesticides are as low as (10^{-1}) M, showcasing the platform's potential for environmental monitoring and food safety applications. Additionally, the reproducibility and stability of the platform were confirmed, making it a reliable tool for field applications using portable Raman spectrometers. Fig. 11.5 illustrates the

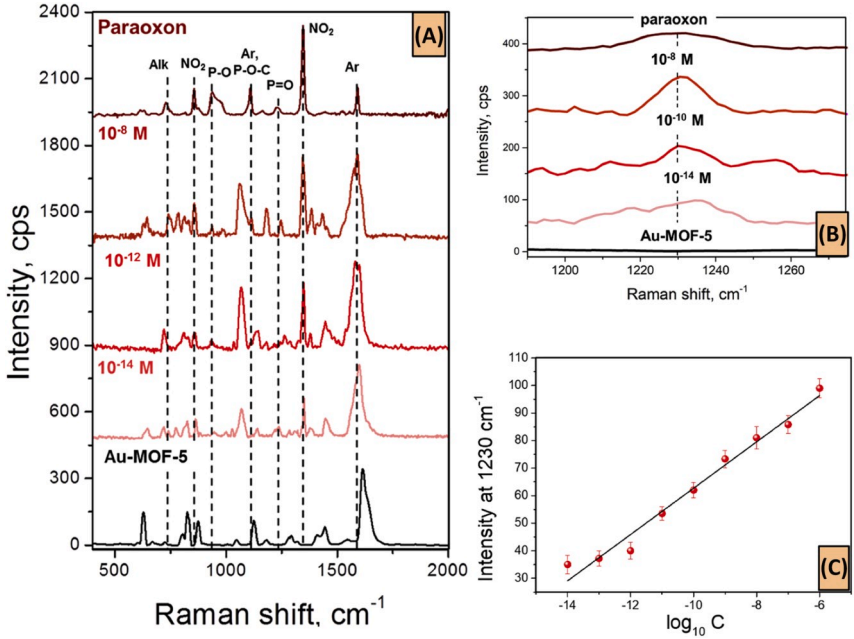


Figure 11.5 Fenitrothion SERS sensing at varying concentrations on gold gratings using MOF-5 film: SERS spectra are shown in (A), the magnified SERS spectrum area (11060–1100 cm^{-1}) is shown in (B), and the related SERS peak intensity dependences on analyte concentration are shown in (C). From Guselnikova, O., Postnikov, P., Elashnikov, R., Miliutina, E., Svorcik, V., & Lyutakov, O. (2019). Metal-organic framework (MOF-5) coated SERS active gold gratings: A platform for the selective detection of organic contaminants in soil. Analytica Chimica Acta, 1068, 70–79. https://doi.org/10.1016/j.aca.2019.03.058.

SERS detection of Fenitrothion on the MOF-5-coated gold gratings. Part A shows the SERS spectra of the substrate with varying Fenitrothion concentrations, demonstrating distinct and identifiable peaks associated with the pesticide's molecular vibrations. Part B magnifies a specific spectral region (1060–1100 cm^{-1}) to highlight peak shifts and intensities correlated with concentration changes. Part C plots the relationship between peak intensity and the logarithm of Fenitrothion concentration, revealing a linear trend with a high correlation coefficient (R^2), confirming the substrate's ability for quantitative analysis. This figure emphasizes the platform's capability to detect Fenitrothion with high sensitivity and specificity, even at ultra-low concentrations, underlining its applicability in environmental sensing and analytical chemistry.

11.5 Lanthanide-based metal-organic framework composites in optical sensors

The rapid industrialization and urbanization of recent decades have escalated the need for effective sensing technologies to monitor harmful organomolecules, which are detrimental to both human health and the environment. Luminescent lanthanide metal organic frameworks (LnMOFs) have emerged as a promising class of materials for organomolecule sensing due to their unique optical and structural properties. Organomolecule sensing is vital in various fields, including environmental monitoring, pharmaceutical analysis, and defense (Chen et al., 2007; Dvries et al., 2014; Li et al., 2022). Toxic molecules, nitroaromatic compounds, and pharmaceuticals often contaminate air, water, and soil, posing significant risks. For instance, exposure to VOCs like benzene and toluene can lead to severe health conditions such as cancer and organ failure. Detecting these compounds at trace levels is crucial to prevent long-term damage (Liu et al., 2016, 2019; Sahoo et al., 2022).

Conventional detection methods, such as liquid chromatography and electrochemical techniques, are reliable but suffer from drawbacks like high costs, time consumption, and complex instrumentation requirements. Spectrofluorometric methods using LnMOFs provide a simpler, faster, and more efficient alternative. LnMOFs combine the advantages of high sensitivity, selectivity, and ease of tunability, making them ideal for sensing applications. LnMOFs are a subclass of MOFs characterized by the incorporation of lanthanide ions (Mahata et al., 2017; Smith et al., 2019; Sun & Yan, 2018). These ions, due to their f-block electronic configuration, exhibit unique luminescence properties, including sharp emission lines, large Stokes shifts, and long lifetimes. The antenna effect, a process in which energy is transferred from an organic linker to the lanthanide ion, enhances their luminescence efficiency. This property is crucial for designing LnMOFs tailored for specific sensing applications. Additionally, LnMOFs' structural diversity enables the creation of frameworks with varying pore sizes and functional groups. This adaptability allows LnMOFs to selectively interact with specific organomolecules, further enhancing their utility as sensors.

The sensing mechanisms of LnMOFs can be broadly categorized into luminescence quenching and enhancement. Quenching occurs when the luminescence intensity decreases upon interaction with an analyte, while enhancement refers to an increase in luminescence. Several processes underlie these phenomena (Mahata et al., 2017):

Static Quenching: Formation of ground-state complexes between the analyte and the LnMOF reduces luminescence intensity.

Dynamic quenching: Interaction between the analyte and excited states of the LnMOF leads to energy dissipation.

Förster resonance energy transfer (FRET): Nonradiative energy transfer from the fluorophore to the analyte occurs when their spectral properties overlap.

Inner filter effect (IFE): The analyte absorbs excitation or emission wavelengths, reducing luminescence.

LnMOFs have demonstrated efficacy in detecting toxic molecules, such as VOCs and pesticides. For example, Tb-based MOFs can selectively detect benzaldehyde and acetone through luminescence quenching mechanisms. The high sensitivity of these frameworks, combined with their ability to function in aqueous and gaseous environments, makes them invaluable for air and water quality monitoring. In the pharmaceutical sector, LnMOFs have been used to detect drugs and metabolites with high specificity. The selective sensing of antibiotics and active pharmaceutical ingredients (APIs) can aid in ensuring drug quality and monitoring therapeutic levels. For instance, Eu-based LnMOFs have been shown to exhibit "turn-on" luminescence in the presence of dipicolinic acid, a biomarker for bacterial spores (Smith et al., 2019; Wei et al., 2022). The detection of nitroaromatic compounds, common precursors to explosives, is another critical application of LnMOFs. LnMOFs can selectively quench luminescence in the presence of these compounds, providing a reliable method for identifying explosive threats in defense and security applications. Despite their potential, several challenges remain in the widespread adoption of LnMOFs for sensing. One primary concern is the stability of LnMOFs in varying environmental conditions. Exposure to humidity, heat, or mechanical stress can degrade their performance (Yan, 2021; Zhang et al., 2013). Efforts are ongoing to develop water-stable and mechanically robust LnMOFs. Scalability is another issue, as synthesizing LnMOFs on an industrial scale remains cost-prohibitive. Advances in green synthesis methods and the use of inexpensive precursors may address this limitation. The integration of LnMOFs with advanced technologies, such as microfluidics and artificial intelligence, represents a promising direction. By combining these frameworks with miniaturized devices and machine learning algorithms, real-time sensing with high accuracy can be achieved (Zhang et al., 2015). In conclusion, luminescent LnMOFs offer a versatile platform for organomolecule sensing, addressing critical challenges in

environmental monitoring, public health, and national security. Continued research and innovation in their design and application will undoubtedly expand their utility, paving the way for smarter and more sustainable sensing solutions.

The study highlights the dual-emitting Eu/Tb(BTC) MOF as a highly sensitive and selective ratiometric fluorescent probe for detecting 2,6-pyridine dicarboxylic acid (DPA), a biomarker of *Bacillus anthracis*. The photoluminescence properties of Eu/Tb(BTC) reveal tunable red and green emissions from Eu^{3+} and Tb^{3+}, respectively, with energy transfer between them modulated by their ratios. Upon DPA binding, the energy transfer is disrupted, quenching Eu^{3+} emission at 618 nm and enhancing Tb^{3+} emission at 547 nm, resulting in a distinct fluorescence color change from red to green (Fig. 11.6). The fluorescence intensity ratio (I547/I618)

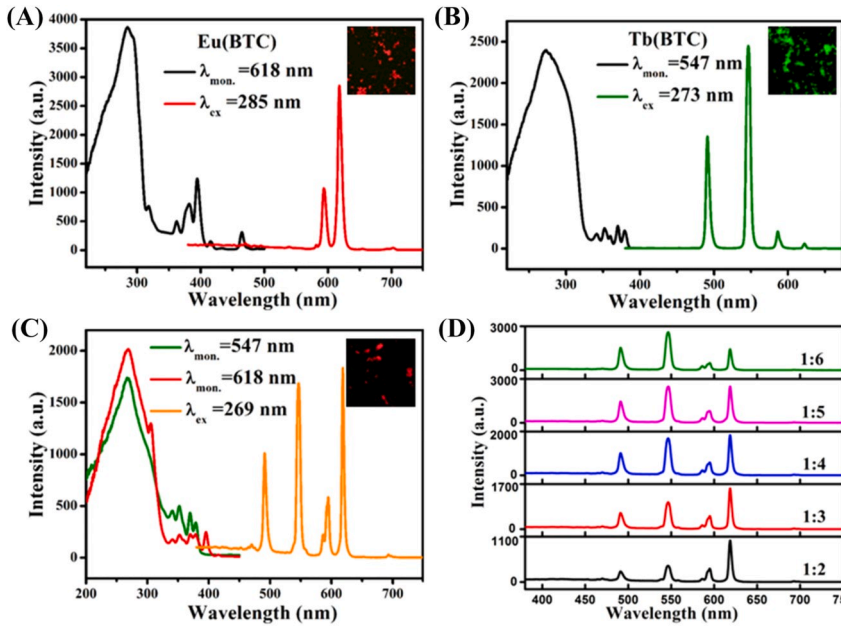


Figure 11.6 Eu(BTC) (A), Tb(BTC) (B), and Eu1Tb4(BTC)5 (C) Photoluminescence excitation (PLE) and Photoluminescence (PL) spectra. The fluorescence microscopic pictures under UV light at 254 nm are displayed in the insets. (D) shows the PL spectra of Eu/Tb(BTC) with varying Eu^{3+}/Tb^{3+} ratios (from 1:2, 1:3, 1:4, 1:5, and 1:6). From Wu, M., Zhuang, Y., Liu, J., Chen, W., Li, X., & Xie, R.-J. (2020). Ratiometric fluorescence detection of 2,6-pyridine dicarboxylic acid with a dual-emitting lanthanide metal-organic framework (MOF). Optical Materials, 106, 110006. https://doi.org/10.1016/j.optmat.2020.110006.

enables quantitative detection with a limit of detection as low as 1087 nM, optimized at an Eu^{3+}/Tb^{3+} ratio of 1:4. The probe demonstrates excellent selectivity for DPA over similar molecules, making it a promising tool for rapid, sensitive, and visually discernible detection of biological threats (Wu et al., 2020).

11.6 Future suggestions

Future research on MOF-based optical sensors should prioritize the development of enhanced water-stable frameworks by introducing novel ligand chemistries and metal-ligand bonds, enabling their application in harsh aqueous environments such as seawater and industrial effluents. Bio-inspired approaches to mimic natural systems can also provide innovative solutions for robust and adaptive stability. Additionally, green synthesis methods, such as using eco-friendly solvents and microwave-assisted techniques, should be explored to reduce the environmental impact of MOF production. Utilizing waste-derived or natural precursors, such as biomass-based ligands, can further promote sustainability in MOF fabrication (Adeel et al., 2021; Hoppe et al., 2018; Rezvani Jalal et al., 2020). Advanced composites combining MOFs with emerging nanomaterials like covalent organic frameworks (COFs), quantum dots, and 2D materials hold promise for synergistic enhancements in optical sensing. Multifunctional composites that integrate sensing with catalytic or adsorptive properties could provide dual applications for pollutant detection and degradation.

The miniaturization and integration of MOFs into wearable and portable sensing devices through thin films, coatings, and membranes remain critical for practical applications. Innovations such as 3D printing of MOF-based materials can enable complex device architectures tailored to specific needs. Combining MOFs with machine learning algorithms can enhance data interpretation, enabling real-time, accurate, and automated sensing systems. The development of self-healing MOF sensors to recover functionality after damage would also enhance long-term usability (Du et al., 2021; Li et al., 2018; Xiao et al., 2022). Expanding the range of sensing targets to emerging contaminants like pharmaceutical residues, microplastics, and nanoparticles, as well as biological targets such as viruses, pathogens, and biomarkers, can broaden MOF applications in environmental monitoring and healthcare diagnostics. Biocompatible and nontoxic MOF formulations could facilitate in vivo sensing for real-time imaging and biomedical monitoring.

Efforts to address industrial scalability challenges must focus on improving the reproducibility and cost-efficiency of MOF synthesis, while collaborations with industry partners can help standardize protocols for MOF-based sensing devices. Designing multistimuli responsive MOFs, capable of reacting to light, temperature, or pH, can enhance versatility, enabling dual-mode or hybrid sensing platforms for detecting multiple analytes (Baghayeri et al., 2020; Chen et al., 2019; Zheng et al., 2018). Regulatory and environmental considerations must also be prioritized by conducting comprehensive toxicological and life-cycle assessments of MOFs to ensure safe use and disposal. Strategies for recycling or regenerating MOFs will be essential to minimize their environmental impact. By addressing these areas, MOF-based optical sensors can advance significantly, contributing to innovative, scalable, and sustainable sensing technologies.

11.7 Conclusion

Strategies such as the use of high-valent metal cations (e.g., Zr(IV), Fe(III)) and hydrophobic linkers have improved MOF resilience in aqueous environments, enabling their use in diverse sensing applications. Tailoring MOF architectures to manipulate luminescence mechanisms, such as FRET and IFEs, has enhanced sensitivity and selectivity for analytes like heavy metals and VOCs. Development of thin films, membranes, and composites has facilitated the practical application of MOFs in portable sensing platforms, with demonstrated success in environmental and biomedical fields. Carbon-based MOF composites, such as graphene/MOF hybrids and lanthanide-doped MOFs, provide robust and multifunctional solutions, achieving detection limits as low as 10^{-9} M for specific pollutants. Continued research focusing on green synthesis, cost-effective scalability, and real-time monitoring technologies is crucial for expanding the practical utility of water-stable MOFs.

References

Adeel, M., Asif, K., Rahman, M. M., Daniele, S., Canzonieri, V., & Rizzolio, F. (2021). Glucose detection devices and methods based on metal–organic frameworks and related materials. *Advanced Functional Materials, 31*(52), 2106023. https://doi.org/10.1002/adfm.202106023.

Anik, Ü., Timur, S., & Dursun, Z. (2019). Metal organic frameworks in electrochemical and optical sensing platforms: A review. *Microchimica Acta, 186*(3), 196. https://doi.org/10.1007/s00604-019-3321-0.

Appelhans, L. N., Hughes, L., McKenzie, B., Rodriguez, M., Griego, J., Briscoe, J., Moorman, M., Frederick, E., & Wright, J. B. (2021). Facile microwave synthesis of

zirconium metal-organic framework thin films on gold and silicon and application to sensor functionalization. *Microporous and Mesoporous Materials, 323*, 111133. https://doi.org/10.1016/j.micromeso.2021.111133.

Baghayeri, M., Ghanei-Motlagh, M., Tayebee, R., Fayazi, M., & Narenji, F. (2020). Application of graphene/zinc-based metal-organic framework nanocomposite for electrochemical sensing of As(III) in water resources. *Analytica Chimica Acta, 1099*, 60–67. https://doi.org/10.1016/j.aca.2019.11.045.

Bodkhe, G. A., Khandagale, D. D., More, M. S., Deshmukh, M. A., Ingle, N. N., Sayyad, P. W., Mahadik, M. M., Shirsat, S. M., Al-Buriahi, M. S., Tsai, M. L., Kim, M., & Shirsat, M. D. (2023). Ag@MOF-199 metal organic framework for selective detection of nickel ions in aqueous media. *Ceramics International, 49*(4), 6772–6779. https://doi.org/10.1016/j.ceramint.2022.10.135.

Chen, B., Yang, Y., Zapata, F., Lin, G., Qian, G., & Lobkovsky, E. B. (2007). Luminescent open metal sites within a metal–organic framework for sensing small molecules. *Advanced Materials, 19*(13), 1693–1696. https://doi.org/10.1002/adma.200601838.

Chen, Y. C., Chiang, W. H., Kurniawan, D., Yeh, P. C., Otake, K. I., & Kung, C. W. (2019). Impregnation of graphene quantum dots into a metal-organic framework to render increased electrical conductivity and activity for electrochemical sensing. *ACS Applied Materials and Interfaces, 11*(38), 35319–35326. https://doi.org/10.1021/acsami.9b11447.

Dong, X. Y., Si, Y., Yang, J. S., Zhang, C., Han, Z., Luo, P., Wang, Z. Y., Zang, S. Q., & Mak, T. C. W. (2020). Ligand engineering to achieve enhanced ratiometric oxygen sensing in a silver cluster-based metal-organic framework. *Nature Communications, 11*(1), 3678. https://doi.org/10.1038/s41467-020-17200-w.

Du, L., Chen, W., Zhu, P., Tian, Y., Chen, Y., & Wu, C. (2021). Applications of functional metal-organic frameworks in biosensors. *Biotechnology Journal, 16*(2), 1900424. https://doi.org/10.1002/biot.201900424.

Du, P., Niu, Q., Chen, J., Chen, Y., Zhao, J., & Lu, X. (2020). "Switch-on" fluorescence detection of glucose with high specificity and sensitivity based on silver nanoparticles supported on porphyrin metal–organic frameworks. *Analytical Chemistry, 92*(11), 7980–7986. https://doi.org/10.1021/acs.analchem.0c01651.

Dvries, R. F., Snejko, N., Iglesias, M., Gutiérrez-Puebla, E., & Monge, M. A. (2014). Ln-MOF pseudo-merohedral twinned crystalline family as solvent-free heterogeneous catalysts. *Crystal Growth and Design, 14*(5), 2516–2521. https://doi.org/10.1021/cg5002336.

Guselnikova, O., Postnikov, P., Elashnikov, R., Miliutina, E., Svorcik, V., & Lyutakov, O. (2019). Metal-organic framework (MOF-5) coated SERS active gold gratings: A platform for the selective detection of organic contaminants in soil. *Analytica Chimica Acta, 1068*, 70–79. https://doi.org/10.1016/j.aca.2019.03.058.

Gutiérrez, M., Martín, C., Souza, B. E., Van der Auweraer, M., Hofkens, J., & Tan, J.-C. (2020). Highly luminescent silver-based MOFs: Scalable eco-friendly synthesis paving the way for photonics sensors and electroluminescent devices. *Applied Materials Today, 21*, 100817. https://doi.org/10.1016/j.apmt.2020.100817.

Hoppe, B., Hindricks, K. D. J., Warwas, D. P., Schulze, H. A., Mohmeyer, A., Pinkvos, T. J., Zailskas, S., Krey, M. R., Belke, C., König, S., Fröba, M., Haug, R. J., & Behrens, P. (2018). Graphene-like metal–organic frameworks: Morphology control, optimization of thin film electrical conductivity and fast sensing applications. *CrystEngComm, 20*(41), 6458–6471. https://doi.org/10.1039/c8ce01264d.

Jalili, R., Khataee, A., Rashidi, M.-R., & Luque, R. (2019). Dual-colored carbon dot encapsulated metal-organic framework for ratiometric detection of glutathione. *Sensors and Actuators B: Chemical, 297*, 126775. https://doi.org/10.1016/j.snb.2019.126775.

Li, B. (2021). Rational design, synthesis, and applications of carbon dots@ metal–organic frameworks (CD@ MOF) based sensors. *TrAC Trends in Analytical Chemistry, 135*, 116163.

Li, G. P., Xie, H. F., Hao, P. F., Fu, Y. L., Zhang, K., Shen, J. J., & Wang, Y. Y. (2022). Size effect of arylenediimide π-conjugate systems on the photoresponsive behaviors in Eu^{3+}-based coordination polymers. *Inorganic Chemistry, 61*(17), 6403–6410. https://doi.org/10.1021/acs.inorgchem.1c03920.

Li, J., Xia, J., Zhang, F., Wang, Z., & Liu, Q. (2018). An electrochemical sensor based on copper-based metal-organic frameworks-graphene composites for determination of dihydroxybenzene isomers in water. *Talanta, 181*, 80–86. https://doi.org/10.1016/j.talanta.2018.01.002.

Liu, W., Dai, X., Wang, Y., Song, L., Zhang, L., Zhang, D., Xie, J., Chen, L., Diwu, J., Wang, J., Chai, Z., & Wang, S. (2019). Ratiometric monitoring of thorium contamination in natural water using a dual-emission luminescent europium organic framework. *Environmental Science and Technology, 53*(1), 332–341. https://doi.org/10.1021/acs.est.8b04728.

Liu, W., Liu, L., Wang, Y., Chen, L., McLeod, J. A., Yang, L., Zhao, J., Liu, Z., Diwu, J., Chai, Z., Albrecht-Schmitt, T. E., Liu, G., & Wang, S. (2016). Tuning mixed-valent Eu^{2+}/Eu^{3+} in strontium formate frameworks for multichannel photoluminescence. *Chemistry—A European Journal, 22*(32), 11170–11175. https://doi.org/10.1002/chem.201602621.

Liu, X., Zhou, Z., Wang, T., Deng, P., & Yan, Y. (2020). Carbon dots incorporated metal–organic framework for enhancing fluorescence detection performance. *Journal of Materials Science, 55*(29), 14153–14165. https://doi.org/10.1007/s10853-020-05027-1.

Mahata, P., Mondal, S. K., Singha, D. K., & Majee, P. (2017). Luminescent rare-earth-based MOFs as optical sensors. *Dalton Transactions, 46*(2), 301–328. https://doi.org/10.1039/C6DT03419E.

Mousavi, A., Zare-Dorabei, R., & Mosavi, S. H. (2020). A novel hybrid fluorescence probe sensor based on metal-organic framework@carbon quantum dots for the highly selective detection of 6-mercaptopurine. *Analytical Methods, 12*(44), 5397–5406. https://doi.org/10.1039/d0ay01592j.

Nie, Y., Tao, X., Zhang, H., Chai, Y.-qin, & Yuan, R. (2021). Self-assembly of gold nanoclusters into a metal–organic framework with efficient electrochemiluminescence and their application for sensitive detection of rutin. *Analytical Chemistry, 93*(7), 3445–3451. https://doi.org/10.1021/acs.analchem.0c04682.

Olorunyomi, J. F., White, J. F., Gengenbach, T. R., Caruso, R. A., & Doherty, C. M. (2022). Fabrication of a reusable carbon dot/gold nanoparticle/metal-organic framework film for fluorescence detection of lead ions in water. *ACS Applied Materials and Interfaces, 14*(31), 35755–35768. https://doi.org/10.1021/acsami.2c09122.

Qian, L.-L. (2020). A 2D copper (I) metal-organic framework: Synthesis, structure and luminescence sensing for cupric, ferric, chromate and TNP. *Dyes and Pigments, 175*, 108159.

Rezvani Jalal, N., Madrakian, T., Afkhami, A., & Ghoorchian, A. (2020). In situ growth of metal-organic framework HKUST-1 on graphene oxide nanoribbons with high electrochemical sensing performance in imatinib determination. *ACS Applied Materials and Interfaces, 12*(4), 4859–4869. https://doi.org/10.1021/acsami.9b18097.

Sahoo, S., Mondal, S., & Sarma, D. (2022). Luminescent lanthanide metal organic frameworks (LnMOFs): A versatile platform towards organomolecule sensing. *Coordination Chemistry Reviews, 470*, 214707. https://doi.org/10.1016/j.ccr.2022.214707.

Sheta, S. M., El-Sheikh, S. M., & Abd-Elzaher, M. M. (2019). Promising photoluminescence optical approach for triiodothyronine hormone determination based on smart copper

metal–organic framework nanoparticles. *Applied Organometallic Chemistry, 33*(9), e5069. https://doi.org/10.1002/aoc.5069.

Smith, J. A., Singh-Wilmot, M. A., Carter, K. P., Cahill, C. L., & Ridenour, J. A. (2019). Lanthanide-2,3,5,6-tetrabromoterephthalic acid metal-organic frameworks: Evolution of halogen···halogen interactions across the lanthanide series and their potential as selective bifunctional sensors for the detection of Fe^{3+}, Cu^{2+}, and nitroaromatics. *Crystal Growth and Design, 19*(1), 305–319. https://doi.org/10.1021/acs.cgd.8b01426.

Sun, N. N., & Yan, B. (2018). A fluorescent probe based on a Tb^{3+}/Cu^{2+} co-functionalized MOF for urinary sarcosine detection. *Analyst, 143*(10), 2349–2355. https://doi.org/10.1039/c8an00425k.

Surya, S. G., Bhanoth, S., Majhi, S. M., More, Y. D., Teja, V. M., & Chappanda, K. N. (2019). A silver nanoparticle-anchored UiO-66(Zr) metal-organic framework (MOF)-based capacitive H_2S gas sensor. *CrystEngComm, 21*(47), 7303–7312. https://doi.org/10.1039/c9ce01323g.

Wang, H., Jiang, S., Xu, Z., zhou, S., & Xu, L. (2022). A novel fluorescent sensor based on a magnetic covalent organic framework-supported, carbon dot-embedded molecularly imprinted composite for the specific optosensing of bisphenol A in foods. *Sensors and Actuators B: Chemical, 361*, 131729. https://doi.org/10.1016/j.snb.2022.131729.

Wei, Q., Wang, C., Zhou, X., Wu, T., Wang, Y., Li, C., & Yang, N. (2019). Ionic liquid and spatially confined gold nanoparticles enhanced photoelectrochemical response of zinc-metal organic frameworks and immunosensing squamous cell carcinoma antigen. *Biosensors and Bioelectronics, 142*, 111540. https://doi.org/10.1016/j.bios.2019.111540.

Wei, X., Zhao, G., Feng, P., Kou, Y., & Tang, Y. (2022). Core–shell lanthanide-doped nanoparticles@Eu-MOF nanocomposites for anticounterfeiting applications. *ACS Applied Nano Materials, 5*(1), 1161–1168. https://doi.org/10.1021/acsanm.1c03751.

Wu, M., Zhuang, Y., Liu, J., Chen, W., Li, X., & Xie, R.-J. (2020). Ratiometric fluorescence detection of 2,6-pyridine dicarboxylic acid with a dual-emitting lanthanide metal-organic framework (MOF). *Optical Materials, 106*, 110006. https://doi.org/10.1016/j.optmat.2020.110006.

Xiao, J., Fan, C., Xu, T., Su, L., & Zhang, X. (2022). An electrochemical wearable sensor for levodopa quantification in sweat based on a metal–organic framework/graphene oxide composite with integrated enzymes. *Sensors and Actuators B: Chemical, 359*, 131586. https://doi.org/10.1016/j.snb.2022.131586.

Xu, L., Pan, M., Fang, G., & Wang, S. (2019). Carbon dots embedded metal-organic framework@molecularly imprinted nanoparticles for highly sensitive and selective detection of quercetin. *Sensors and Actuators B: Chemical, 286*, 321–327. https://doi.org/10.1016/j.snb.2019.01.156.

Xuan, T., Gao, Y., Cai, Y., Guo, X., Wen, Y., & Yang, H. (2019). Fabrication and characterization of the stable Ag-Au-metal-organic-frameworks: An application for sensitive detection of thiabendazole. *Sensors and Actuators B: Chemical, 293*, 289–295. https://doi.org/10.1016/j.snb.2019.05.017.

Yan, B. (2021). Luminescence response mode and chemical sensing mechanism for lanthanide-functionalized metal–organic framework hybrids. *Inorganic Chemistry Frontiers, 8*(1), 201–233. https://doi.org/10.1039/d0qi01153c.

Yan, F., Wang, X., Wang, Y., Yi, C., Xu, M., & Xu, J. (2022). Sensing performance and mechanism of carbon dots encapsulated into metal–organic frameworks. *Microchimica Acta, 189*(10), 379. https://doi.org/10.1007/s00604-022-05481-5.

Yang, X., Liu, Y., Lam, S. H., Wang, J., Wen, S., Yam, C., Shao, L., & Wang, J. (2021). Site-selective deposition of metal-organic frameworks on gold nanobipyramids for surface-enhanced Raman scattering. *Nano Letters, 21*(19), 8205–8212. https://doi.org/10.1021/acs.nanolett.1c02649.

Zhang, Y., Geng, D., Kang, X., Shang, M., Wu, Y., Li, X., Lian, H., Cheng, Z., & Lin, J. (2013). Rapid, large-scale, morphology-controllable synthesis of YOF:Ln^{3+} (Ln=Tb, Eu, Tm, Dy, Ho, Sm) nano-/microstructures with multicolor-tunable emission properties. *Inorganic Chemistry, 52*(22), 12986–12994. https://doi.org/10.1021/ic401501t.

Zhang, Y., Li, X., Li, K., Lian, H., Shang, M., & Lin, J. (2015). Crystal-site engineering control for the reduction of Eu^{3+} to Eu^{2+} in $CaYAlO_4$: Structure refinement and tunable emission properties. *ACS Applied Materials & Interfaces, 7*(4), 2715–2725. https://doi.org/10.1021/am508859c.

Zhang, Y., Sun, M., Peng, M., Du, E., Xu, X., & Wang, C.-C. (2023). The fabrication strategies and enhanced performances of metal-organic frameworks and carbon dots composites: State of the art review. *Chinese Chemical Letters, 34*(3), 107478. https://doi.org/10.1016/j.cclet.2022.04.076.

Zheng, Y., Sun, F.-Z., Han, X., Xu, J., & Bu, X.-H. (2020). Recent progress in 2D metal-organic frameworks for optical applications. *Advanced Optical Materials, 8*(13), 2000110. https://doi.org/10.1002/adom.202000110.

Zheng, Y., Zheng, S., Xue, H., & Pang, H. (2018). Metal-organic frameworks/graphene-based materials: Preparations and applications. *Advanced Functional Materials, 28*(47), 1804950. https://doi.org/10.1002/adfm.201804950.

Zhou, X., Wang, X., & Shang, L. (2023). Ratiometric fluorescence and visual sensing of ATP based on gold nanocluster-encapsulated metal-organic framework with a smartphone. *Chinese Chemical Letters, 34*(8), 108093. https://doi.org/10.1016/j.cclet.2022.108093.