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Research progress on metal-organic frameworks in fluorescent detection of biomarkers

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Abstract. Biomarkers act as "molecular probes" in disease diagnosis and play a pivotal role in disease diagnosis, prognostic evaluation, and monitoring of treatment efficacy. Traditional detection techniques like LC-MS/MS and ELISA come with limitations including high costs, prolonged testing durations, and elevated false-positive rates, these features have spurred the rapid advancement of fluorescent detection technologies. As an emerging class of fluorescent sensing materials, metal-organic frameworks (MOFs) possess unique structural designability, ultra-high specific surface area, and excellent biocompatibility, thereby exhibiting significant application potential in the field of biomarker fluorescent detection. This paper systematically reviews three major categories of biomarkers selected from a broad spectrum of biomarker types: pathogen-related biomarkers (anthrax biomarker pyridine-2,6-dicarboxylic acid (DPA)); disease metabolism-related biomarkers (carcinoid syndrome biomarkers 3-(2-aminoethyl)-1H-indol-5-ol (5-HT) and 2-(5-hydroxy-1H-indol-3-yl)acetic acid (5-HIAA), environmental toxin metabolite pyren-1-ol (1-HP), and amino acid metabolites 4-(2-aminoethyl)-2-methoxyphenol (3-MT) and histidine (His)); and nutrition and health-related biomarkers (2- (3, 4-dihydroxyphenyl)-3,5,7-trihydroxy-4H-chromen-4-one (Que)). Fluorescence detection technology based on metal-organic frameworks (MOFs) enables highly sensitive detection at the nM-μM level. Its mechanisms include host-guest recognition via hydrogen bonding and π-π stacking, photoinduced electron transfer (PET), and energy transfer (IFE, FRET), providing a technical foundation for the development of comprehensive detection systems. Although MOF-based fluorescent sensing technology holds great promise, it still faces challenges such as stability, biosafety, and application conversion. In the future, efforts should be made to optimize materials, improve safety assessment systems, and integrate equipment to accelerate the industrialization of MOF-based fluorescent sensing technology in precision medicine and disease diagnosis.

Keywords: Metal-organic frameworks, Fluorescence detection, Biomarkers, Sensing mechanisms, Precision medicine.

1. Introduction

Biomarkers act as "molecular probes" in disease diagnosis and play a crucial role in disease diagnosis, prognostic assessment, and monitoring of treatment efficacy. They mainly include pathogen-related biomarkers (anthrax biomarkers), disease metabolism-related biomarkers (tumor metabolites, neurotransmitter metabolites), and nutrition and health-related biomarkers (plant-derived bioactive compounds). 4-(2-aminoethyl)-2-methoxyphenol (3-MT), a key metabolite of dopamine, plays a significant role in the diagnosis of neuroendocrine tumors such as pheochromocytoma through the detection of its levels in urine. It is one of the catecholamine metabolic biomarkers that warrant attention in clinical practice [1]. Similarly, elevated serum 2-hydroxyglutaric acid (2-HG) concentrations are a specific indicator of glioma, while abnormal levels of 5-hydroxyindoleacetic acid (5-HIAA) in urine are closely associated with carcinoid syndrome. However, when detecting biomarkers, one often encounters the challenge of interference from low-abundance target molecules in complex biological samples (such as serum and saliva), which places extremely high demands on the sensitivity and selectivity of detection technologies. Traditional detection techniques like liquid chromatography-tandem mass spectrometry (LC-MS/MS), despite their high specificity, have significant limitations in practical applications. Taking 3-MT detection as an example, although LC-

MS/MS technology offers high specificity, it faces challenges in practical use. Steps such as derivatization in sample preparation may introduce interference, affecting the stability of recovery rates for endogenous substances, and the detection process is time-consuming [2]. Moreover, enzyme-linked immunosorbent assay (ELISA) has limited ability to distinguish structural analogues due to antibody cross-reactivity, often leading to false-positive results. In contrast, fluorescence sensing technology boasts significant advantages in point-of-care testing (POCT) owing to its high sensitivity (with detection limits as low as the fM level), rapid response, and suitability for on-site testing. For example, a dual-mode fluorescence sensing platform based on a "noise purifier" enables ultra-sensitive on-site detection, while ratiometric fluorescence sensors combined with smart devices are also attracting attention for their strong anti-interference capability [3][4].

Metal-Organic Frameworks (MOFs) are porous crystalline structures self-assembled from metal ions/clusters (Al^{3+}, Zr^{4+}) and polyhedral organic ligands (terephthalic acid, imidazole) via coordination bonds. As an emerging class of fluorescent sensing materials, MOFs exhibit substantial application potential in biomarker fluorescent detection, thanks to their unique structural features and excellent optical properties, thereby offering crucial support for the advancement of disease diagnostic technologies. Specifically, MOF-based fluorescent sensing platforms have been extensively explored and applied due to their multiple advantages: (1) They possess an ultra-high specific surface area and tunable porosity, providing abundant active sites for molecular recognition [5]; (2) The pore size can be regulated within a certain range, enabling the screening of biomolecules (selectively excluding large-molecule interferents); (3) Their surfaces contain functional groups such as carboxyl and amino groups, allowing for the specific capture of target molecules through hydrogen bonding or π-π stacking. For instance, Ln(III)-functionalized MOF systems can amplify fluorescence signals via energy transfer between ligands and lanthanide ions (the "antenna effect"), while reducing background interference through interactions between pore sites and target molecules, thus significantly enhancing detection performance [6].

In recent years, functionalization strategies have continuously expanded the application potential of MOFs in the sensing field. Studies have demonstrated that highly selective detection of specific target substances can be achieved by designing the interaction mechanism between ligands and metal ions in luminescent metal-organic frameworks [7]. For example, sensing systems constructed based on principles such as energy transfer between ligands and metal ions can effectively enhance detection performance, providing a feasible approach for the precise detection of biomarkers. Dual-emission systems, leveraging their self-calibration mechanisms, show advantages in addressing interference from complex biological matrices. For instance, a luminescent metal-organic framework with dual-emission properties can realize ratiometric sensing of target molecules through relevant regulation, offering insights for the precise detection of substances in biological samples [8]. However, MOFs still encounter challenges in practical applications: firstly, the pore size characteristics of MOFs may affect their performance, and research on pore size engineering provides a direction for solving such issues [9]; secondly, some MOFs exhibit non-specific adsorption based on hydrophobic interactions, which may introduce errors [10]; thirdly, microfluidic devices based on MOFs still require optimization of critical components such as signal transmission in detection applications[11]. This paper systematically analyzes the "structure-function-mechanism" correlation of MOFs, focusing on their innovative applications in the fluorescent detection of biomarkers, aiming to provide sufficient theoretical support and guidance for the development of highly reliable diagnostic tools. By in-depth analysis of molecular recognition mechanisms based on host-guest interactions such as hydrogen bonding and π-π stacking, the fluorescence regulation mechanism of photoinduced electron transfer (PET), and energy transfer response mechanisms including the internal filtration effect (IFE) and fluorescence resonance energy transfer (FRET), this study reveals the molecular mechanisms by which MOFs achieve high-sensitivity detection at the nM-μM level, thus providing a crucial theoretical basis for constructing highly selective and rapid-response fluorescent sensing platforms.

2. Advantages of MOFs for fluorescent detection of biomarkers

2.1. Structural designability

The modular synthesis strategy of metal-organic frameworks (MOFs) endows them with highly tunable structural properties. By selecting organic ligands with specific functionalities (carboxylic acid ligands containing benzothiadiazole units) and combining them with metal nodes, the pore size, surface chemistry, and fluorescence response properties of MOFs can be selectively regulated. Li Yu and colleagues employed 5,5'-benzothiadiazole-4,7-bis (benzoic acid) (H_4BTDI) as the main ligand and introduced bisimidazole-type auxiliary ligands, successfully constructing transition/rare earth metal coordination polymers with different dimensions. This structural design not only enhances the rigidity of the π-conjugated system in the coordination polymer but also achieves highly selective fluorescence responses to Cr^{3+} and $H_2PO_4^-$ through diverse coordination modes, with detection limits as low as 0.74 μM and 0.50 μM, respectively [12]. This "ligand-metal" synergistic regulation strategy provides a theoretical basis and a solid foundation for the future development of fluorescent probes targeting specific biomarkers.

2.2. High specific surface area

The porous nature of MOFs endows them with an extremely high specific surface area (typically ranging from 1000 to 6000 m^2/g), which provides abundant active sites for the adsorption and enrichment of biomarkers. He Qiqi et al. reported lanthanide-based MOFs derived from benzothiadiazole dimethylene. Their three-dimensional pore structure effectively adsorbs ions such as Fe^{3+} and $Cr_2O_7^{2-}$, and induces significant fluorescence quenching effects through host-guest interactions, achieving a detection limit as low as 0.94 μM for Fe^{3+} [13]. Additionally, research by Tian Xuemei et al. demonstrated that Zn-MOFs containing bisimidazole-benzothiadiazole ligands, due to their high porosity, can simultaneously detect multiple metal ions (Fe^{3+}, Cr^{3+}, Al^{3+}), showcasing the advantage of "one probe, multiple targets" [14]. This high specific surface area significantly enhances detection sensitivity, especially in the detection of trace biomarkers, where it exhibits extremely high sensitivity.

2.3. Good biocompatibility

Metal-organic frameworks (MOFs) exhibit excellent biocompatibility in the fluorescent detection of biomarkers, enabling them to adapt to complex biological environments and minimize interference with biological systems. For instance, the Zn-MOF (JXUST-53) developed by Jiangxi University of Science and Technology remains stable after being soaked in aqueous solutions and organic solvents at different pH levels (1–12) for more than 24 hours. It maintains over 90% cell viability in MCF-7 cells and can enter cells to detect biomarkers such as L-Thr [15]. Additionally, sensors prepared by loading ZIF-8 with organic fluorescent molecules can be used for in vivo detection of carboxylesterase 1, thanks to ZIF-8's excellent biocompatibility. These findings indicate that MOFs can stably exist within biological systems and perform detection functions [16]. Such characteristics grant MOFs significant application potential in complex and dynamic biological environments.

3. Research progress on MOFs fluorescence detection of different types of biomarkers

MOF-based fluorescent sensing technology has made significant progress in the field of biomarker detection due to its unique organic-inorganic hybrid structure and diverse photophysical properties. Biomarkers, which serve as measurable indicators reflecting normal or pathological processes in living organisms, are highly diverse in type and function. Three key categories of biomarkers—pathogen-related biomarkers, disease metabolism-related biomarkers, and nutrition and health-related biomarkers—have been selected as the primary focus of research. Comprehensive analysis indicates that MOFs fluorescence detection technology has established a relatively complete biomarker detection system, with technical characteristics showing trends toward diversified detection mechanisms, high sensitivity (nM-μM level), and broadened application areas, laying a solid foundation for industrial applications in precision medicine, biosafety, and food safety.

3.1. Pathogen-related biomarker detection

Taking anthrax biomarker pyridine-2,6-dicarboxylic acid (DPA) as a typical example, a comprehensive technical system has been developed. As a specific biomarker for Bacillus anthracis spores, the accurate detection of DPA is of great significance for biosafety protection. Sensors based on fluorescence enhancement mechanisms exhibit rapid response advantages. Cong et al. (2022) developed three novel MOFs with a detection limit of 1.01×10^{-6} M for DPA, achieving recovery rates of 90-115% in fetal bovine serum and response times of less than 30 seconds [17]. Lanthanide MOFs, leveraging their unique antenna effect, have emerged as important detection platforms. Wang et al. (2024) achieved a detection limit of 0.41 μM using a Eu^{3+}-based dual-ligand MOF, enabling visual detection via color changes, and successfully prepared a portable PVA@Eu-MOF membrane [18]. Ratio-based fluorescence technology further enhances detection accuracy. Zhang, Zhou, et al. (2018) achieved a detection limit of 3.6 nM with Tb^{3+}-functionalized MOF composites, demonstrating good recovery rates in human serum [19]. Zhang, Hao et al. (2025) designed the Eu-TDA-DHTP probe, which innovatively achieved dual-mode detection in fluorescence mode (1.9 μmol/L) and colorimetric mode (5 μmol/L), combining a smartphone platform to provide a new solution for on-site rapid detection [20].

3.2. Disease Metabolism-Related Biomarker Testing

Disease-related metabolic biomarkers encompass several important categories, including tumor metabolites, environmental toxin metabolites, and amino acid metabolites. For carcinoid syndrome biomarkers, pyridine-2,6-dicarboxylic acid (5-HT) and 2-(5-hydroxy-1H-indol-3-yl) acetic acid (5-HIAA) act as specific metabolic markers for carcinoid tumors, and their detection is of great significance for early tumor diagnosis. Liu Ji and colleagues synthesized two cadmium-based MOFs (LCU-129 and LCU-130). Both MOFs achieved highly selective fluorescence detection of 5-HT and 5-HIAA. Specifically, LCU-129 exhibited detection limits as low as 0.06 μM and 0.19 μM for 5-HT and 5-HIAA, respectively, while LCU-130 showed detection limits of 1.17 μM and 2.23 μM for 5-HT and 5-HIAA, respectively [21]. Additionally, due to the functional groups in the MOFs (those in LCU-129), the material achieved highly selective fluorescence enhancement toward Al^{3+} through a fluorescence enhancement mechanism, with a detection limit as low as 0.74 μM. Both MOFs displayed distinct fluorescence enhancement and quenching effects, further demonstrating their versatile sensing capabilities. Ying et al. (2021) constructed a zinc-based MOF using a tetraphenypyridine ligand. Through in-situ doping, the MOF achieved a fluorescence quantum yield of 20.3% and exhibited selective fluorescence quenching toward 5-HT and 5-HIAA, with detection limits of 0.50 μM and 0.57 μM, respectively. This performance is attributed to mechanisms involving energy transfer and competitive light absorption [22].For environmental exposure biomarkers, pyren-1-ol(1-HP) serves as a metabolic marker for polycyclic aromatic hydrocarbon (PAH) exposure, where its urinary concentration reflects the extent of exposure to environmental PAH pollutants. Liu Xu and colleagues constructed a Eu^{3+}-based MOF using a functional ligand, which enabled highly selective fluorescence detection of 1-hydroxypyrene and tryptophan metabolites, with detection limits of 1.10 μM and 0.73 μM, respectively [23]. Song Lijun (2021) developed five functionalized MOFs through post-synthetic modification strategies, which exhibited selective fluorescence responses toward multiple L-tryptophan(Trp) biomarkers (including 3-methoxytyramine and histidine (His)) in serum and urine samples, with the Eu/biimidazole MOF achieving a detection limit of 0.18 μM for histidine [24].

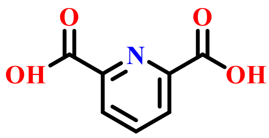
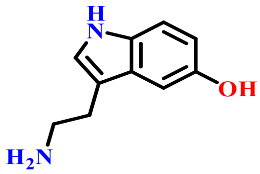
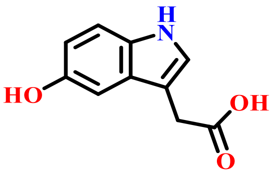
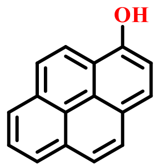
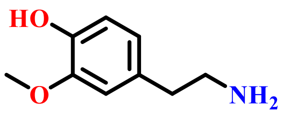
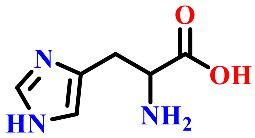
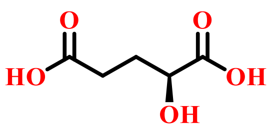
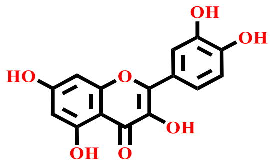
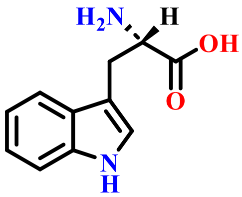
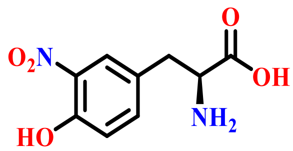
3.3. Nutrition and health-related biomarkers

The detection technologies for nutrition- and health-related biomarkers vividly demonstrate the application value of MOFs in nutritional assessment and health monitoring. 2-(3,4-dihydroxyphenyl)-

3,5,7-trihydroxy-4H-chromen-4-one (Que), a prominent flavonoid bioactive compound of plant origin, is widely distributed in tea, red wine, and fruits and vegetables. It exhibits multiple biological activities, including anti-inflammatory and anti-cancer properties, and serves as a key biomarker for evaluating the antioxidant capacity and nutritional functions of food products.Bhat et al. (2024) reported that europium-based three-dimensional MOFs (ZEuMOF), synthesized via a sol-gel method, achieved a highly sensitive fluorescence response to quercetin with a detection limit as low as 9.86 × 10^{-7} M. Through DFT calculations and spectral analysis, they confirmed that the internal filtration effect (IFE) acts as the primary quenching mechanism. Notably, the detection results of quercetin in green tea samples were consistent with those obtained via HPLC, and the material maintained stable performance even after multiple reuse cycles [25]. Feng and colleagues synthesized a nano-Zr-based MOF (nano-Zr-MOF) using a one-pot method and found it exhibits excellent water dispersibility and strong red fluorescence emission. This MOF enables simultaneous fluorescence detection of quercetin and Hg^{2+} with detection limits as low as 0.026 μM and 0.039 μM, respectively. Mechanistic studies revealed that fluorescence quenching arises from the synergistic effects of static quenching, photoinduced electron transfer (PET), and internal filtration [26]. Such research highlights the potential of MOFs as versatile platforms for detecting specific nutritional biomarkers.

To provide a more intuitive illustration of the structural characteristics and diversity of these biomarkers, Table 1 systematically summarizes the molecular structural formulas of all important biomarkers discussed in this paper, including their full names, abbreviations, and chemical structures, providing readers with an important reference for understanding the structure-function relationships of different types of biomarkers.

Table 1. Structural formula of biomarkers.

Full name	Abbrev.	Structural formula	Full name	Abbrev	Structural formula
pyridine-2,6-dicarboxylic acid	DPA		3-(2-aminoethyl)-1H-indol-5-ol	5-HT	
2-(5-hydroxy-1H-indol-3-yl)acetic acid	5-HIAA		pyren-1-ol	1-HP	
4-(2-aminoethyl)-2-methoxyphenol	3-MT		histidine	His	
(S)-2-hydroxypentanedioic acid	2-HG		2-(3,4-dihydroxyphenyl)-3,5,7-trihydroxy-4H-chromen-4-one	Que	
L-tryptophan	Trp		(S)-2-amino-3-(4-hydroxy-3-nitrophenyl)propanoic acid	3-NT	

4. Mechanism of action of MOFs-based fluorescent detection of biomarkers

The ability of metal-organic framework materials to efficiently detect biomarkers via fluorescence is primarily due to the exceptional properties conferred by their unique organic-inorganic hybrid structure. This novel porous coordination polymer forms highly ordered crystalline structures through the self-assembly of metal ions or metal clusters with organic ligands, exhibiting extremely high specific surface area (up to 90% free volume), tunable pore size, excellent chemical stability, and easily functionalizable surface properties. Through synthesis strategies such as sol-gel, microwave synthesis, and mechanochemistry, researchers can control the structural parameters of MOFs, including pore size, morphology, and surface chemical properties, thereby achieving selective recognition and highly sensitive detection of different biomarkers.

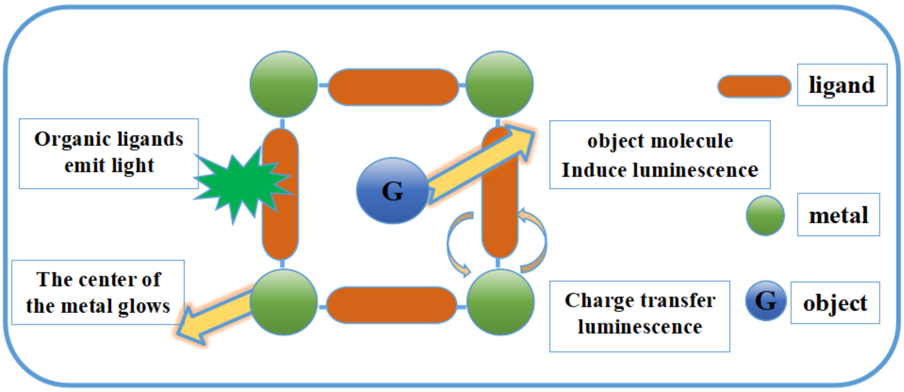


Figure 1. Different forms of luminescence in MOFs.

As illustrated in Figure 1, the fluorescence origins of metal-organic frameworks (MOFs) can be categorized into four types: luminescence from organic ligands, luminescence from metal centers, charge-transfer-induced luminescence, and guest molecule-induced luminescence (luminescence triggered by the introduction of lanthanide metal ions or dye molecules). The interaction between target biomarkers and MOFs induces characteristic changes in fluorescence intensity, enabling high-sensitivity quantitative detection of biomarkers based on such fluorescence responses. Currently, MOF-based fluorescent sensing technologies have evolved multiple detection modes, including fluorescence enhancement, fluorescence quenching, and ratiometric fluorescence. The primary fluorescence response mechanisms involve three categories: host-guest interaction mechanisms, energy transfer mechanisms, and photoinduced electron transfer (PET) mechanisms. Through rational design of metal nodes, optimization of ligand structures, regulation of pore sizes, and functional modification, high-performance sensing platforms targeting specific biomarkers can be constructed. This material design strategy, rooted in a clear understanding of the underlying mechanisms, has promoted the application of MOF sensors in biomedical diagnostics—such as pathogen detection and tumor marker screening—and laid a theoretical foundation for the development of intelligent, multifunctional biosensing technologies.

4.1. Mechanism of interaction between subject and object

The interaction between MOFs and biomarkers is key to achieving selective detection. This molecular recognition process is primarily achieved through various noncovalent interaction mechanisms, including hydrogen bonding, π-π stacking, hydrophobic interactions, and coordination bonding. Hydrogen bonding typically occurs between biomarkers containing functional groups such as hydroxyl, carboxyl, or amino groups and MOF ligands or metal nodes, exhibiting directional and selective characteristics; π-π stacking interactions primarily exist between analytes with aromatic ring structures and MOF ligands, forming stable bonds through electron cloud overlap; coordination bonding occurs between biomarkers containing lone pairs of electrons and metal nodes, forming relatively strong interactions. The sensing platform developed by Miller et al. (2016) based on UiO-66-NH_2 effectively validated this mechanism, which uses thymidine-rich FAM-labeled ssDNA to detect Hg^{2+}. The ssDNA binds to the MOF through hydrogen bonds and π-π stacking interactions between DNA bases and aromatic groups on the organic linker molecules, with the amino group on the ligand serving as an “anchor” on the MOF surface. The fluorescence of the FAM group is quenched through photoinduced electron transfer, achieving an efficiency of up to 75% [27].

4.2. Energy transfer

The internal filtering effect (IFE) represents a critical energy transfer mechanism in MOF-based sensors. Sankhla and colleagues (2024) extensively elaborated on IFE as a key mechanism in MOF optical sensing, which operates through the absorption of the MOF's fluorescent emission by the analyte or competitive absorption of excitation light between the analyte and MOF. Unlike photoinduced electron transfer (PET), IFE is independent of the distance between the MOF and analyte, relying instead on spectral overlap between the analyte's absorption and the MOF's emission or excitation spectra [28]. Li and coworkers (2024) constructed a copper-based MOF (CuMOF) capable of detecting the oxidative stress biomarker (S)-2-amino-3-(4-hydroxy-3-nitrophenyl) propanoic acid (3-NT). This design revealed that the fluorescence quenching behavior is jointly determined by the internal filtering effect and other mechanisms, enabling the MOF to achieve a detection limit of 110.8 ng mL^{-1} for 3-NT in diluted serum and urine samples [29]. Such findings highlight the significant role of the internal filtering effect in facilitating fluorescence-based detection of specific biomarkers within complex biological samples.

4.3. Photoinduced Electron Transfer (PET)

The modular synthesis strategy of metal-organic frameworks (MOFs) endows them with tunable fluorescence properties, which is crucial for the detection of specific biomarkers. Based on a review by Karmakar et al. (2022) published in National Science Review, fluorescence-based MOF sensing methods exhibit excellent performance in trace-level selective detection, with fluorescence resonance energy transfer (FRET) and photoinduced electron transfer (PET) being the dominant mechanisms [30]. In the PET mechanism, the regulation of fluorescence properties relies on precise matching of the HOMO-LUMO energy levels between organic ligands and analytes. Niu and colleagues (2023) further revealed that when the LUMO energy level of the analyte differs from that of the MOF ligand, distinct fluorescence responses can be triggered: energy level matching induces fluorescence quenching through electron transfer, while mismatched energy levels lead to fluorescence enhancement [31]. Hong et al. (2023) utilized density functional theory calculations to elucidate the specific mechanism by which a Zn (II)-based MOF selectively detects anthrax-related biomarkers. They found that since the LUMO energy level of the ligand is higher than that of $H_2PO_4^-$, photoinduced electron transfer occurs from the ligand to $H_2PO_4^-$, resulting in a transition from fluorescence quenching to enhancement [32]. Additionally, Geng and coworkers developed a three-dimensional Zn-MOF that enables efficient detection of the oxidative stress biomarker (S)-2-amino-3-(4-hydroxy-3-nitrophenyl)propanoic acid (3-NT) via the PET mechanism, with a detection limit as low as 0.31 μM and a rapid response time of 24 seconds [33]. This PET-based design strategy highlights the advantages of MOFs in rapid biomarker detection, offering valuable insights for the rational design of high-performance fluorescent sensors.

5. Challenges and Outlook

5.1. Challenges

Metal-organic frameworks (MOFs) show significant potential in fluorescent detection of biomarkers, but their practical application still faces three core challenges: (1) Insufficient structural stability—under complex physiological conditions such as high humidity, high salt concentration, and pH fluctuations, some MOFs are prone to structural changes, leading to unstable fluorescent performance, which directly affects the accuracy and reproducibility of detection; (2) Questions about biosafety: While some MOFs exhibit good biocompatibility, the long-term toxicity of their metabolic byproducts and the biological effects of prolonged exposure remain unclear, with no systematic assessments available; (3) Delayed industrialization: Current research is largely confined to the laboratory stage. When transitioning to clinical or point-of-care testing, issues such as insufficient device integration, lack of portability, and absence of standardized testing protocols become prominent, severely hindering technological implementation.

5.2. Outlook

In response to the aforementioned challenges, this paper proposes three breakthrough directions: (1) Material engineering optimization, through structural optimization and functional design to develop highly stable MOFs, ensuring their long-term structural and fluorescent performance stability in complex physiological environments; (2) Safety system construction, conducting systematic biosafety research to establish a long-term safety assessment framework covering both MOFs and their metabolic products, laying the safety foundation for clinical applications; (3) Industry-academia-research collaboration and technology transfer, driving the upgrading of detection devices toward miniaturization, integration, and intelligence, establishing standardized detection procedures and quality control systems, and accelerating the transition of technology from the laboratory to clinical and on-site detection. This paper argues that through the aforementioned strategies, MOF fluorescent sensing technology will achieve industrial breakthroughs in precision medicine, early disease diagnosis, and health monitoring, playing a pivotal role.

6. Conclusions

Metal-organic frameworks (MOFs) have emerged as promising fluorescent sensing materials, exhibiting significant advantages and broad application prospects in biomarker detection. This paper systematically elaborates on the unique merits of MOFs, including their structural designability, high specific surface area, and excellent biocompatibility. It also conducts an in-depth analysis of their research progress in detecting three categories of biomarkers: pathogen-related, disease metabolism-related, and nutrition and health-related biomarkers. Furthermore, the core mechanisms involved—such as host-guest interactions, energy transfer, and light-induced electron transfer—are detailedly explained. Through in-depth exploration of the "structure-function-mechanism" correlation of MOFs, coupled with continuous efforts to address existing challenges (stability, biosafety, and application translation), MOF-based fluorescent sensing technology is expected to play an increasingly crucial role in precision medicine fields, including disease diagnosis, prognosis assessment, and treatment efficacy monitoring. This will provide robust technical support for the development of efficient, portable, and reliable biomarker detection platforms.

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