CrystEngComm

HIGHLIGHT

View Article Online
View Journal | View Issue

Cite this: *CrystEngComm*, 2025, **27**, 4443

Received 5th May 2025,
Accepted 27th May 2025

DOI: 10.1039/d5ce00469a

rsc.li/crystengcomm

MOFs in healthcare diagnostics: shaping the future of biomedical test strips

Vibhav Shukla and Kafeel Ahmad Siddiqui *

The integration of metal–organic frameworks (MOFs) into biomedical diagnostics offers a promising approach to enhancing sensitivity, selectivity, and sustainability in test strip technology. MOFs, with their high porosity, tunable functionality, and exceptional luminescent properties, provide an innovative platform for developing next-generation biosensors. Their ability to interact with specific biomarkers enables highly accurate and rapid detection of health-related analytes, such as glucose, in real urine samples. Additionally, the catalytic properties of MOFs enhance degradation mechanisms, making them suitable for environmental applications like wastewater treatment. This highlight examines how MOFs and their derived composites are reshaping the design and functionality of biomedical test strips, offering a glimpse into a more efficient and eco-conscious future in diagnostics. By leveraging their multifunctionality, MOFs can improve the sensitivity of diagnostic platforms while reducing reliance on conventional materials, aligning with the growing demand for greener and more effective healthcare solutions.

1. Introduction

Biomedical test strips are vital tools for diagnostics, commonly used for glucose monitoring, pregnancy tests, and detecting infections.[1] They operate by triggering chemical reactions to produce readable signals, indicating the presence or levels of specific substances.[2] However, existing test strips often encounter challenges, including environmental concerns, high costs, and limitations in detection accuracy or complexity.[3]

Metal–organic frameworks (MOFs), composed of metal ions or clusters and organic ligands, feature highly porous structures that allow precise control over size, shape, surface area, porosity, and chemical properties (Scheme 1).[4] These characteristics make MOFs highly suitable for biomedical test strips, as they provide improved sensitivity, rapid detection, and eco-friendly advantages.[4] Despite the widespread use of diagnostic strips, there exists a clear market gap in delivering portable, eco-friendly, and highly sensitive diagnostic tools suitable for real-world conditions, especially in resource-constrained environments. Existing enzyme-based test strips often suffer from limited analyte specificity, poor long-term stability, and environmental concerns related to chemical waste and disposable plastic substrates.[5] Their tunable frameworks enable the synthesis of 1D, 2D, and 3D structures, making them highly versatile for biomedical applications. MOFs are commonly integrated into the sensing elements of test strips to enhance analyte detection using optical, electrochemical, or colorimetric signals.[6]

Traditional test strips rely on straightforward chemical reactions that produce a visual or colorimetric response. While these methods are cost-effective and user-friendly, they face several drawbacks, including:

- Low sensitivity: detecting trace amounts of analytes remains challenging with traditional methods.
- Environmental concerns: many conventional test strips contain toxic substances or pose disposal issues.
- Design challenges: developing test strips capable of detecting a wide range of analytes with high precision and sensitivity is a complex engineering task.

To address these challenges, recent advancements in colorimetric biosensing have introduced a highly efficient and rapid detection method. Unlike conventional peroxide-based colorimetric assays, which require hydrogen peroxide and oxygen, this novel approach utilizes a single-step enzyme reaction, where an oxidoreductase enzyme transfers electrons to a coloring reagent *via* a metal complex mediator. This technique significantly enhances detection speed (within ~5 seconds) and accuracy, eliminating oxygen dependency and reducing measurement inconsistencies. The integration of MOFs with such next-generation colorimetric sensors further strengthens the sensitivity and stability of test strips. MOF-based systems offer high selectivity, enabling the detection of low analyte concentrations with exceptional precision.[7] Additionally, by incorporating iron, ruthenium, osmium, and copper complexes as mediators, the new method ensures enhanced signal output and cost-effectiveness. Thus, the

---

Department of Chemistry, National Institute of Technology Raipur, GE Road Raipur, 492010, Chhattisgarh, India. E-mail: kasiddiqui.chy@nitrr.ac.in

synergistic combination of MOFs and advanced colorimetric techniques presents a transformative approach in biomedical diagnostics, paving the way for highly sensitive, rapid, and sustainable test strip technologies.[8]

2. Benefits of MOFs in test strip development

The global diagnostic biosensor market, particularly in point-of-care testing and wearable platforms, is projected to surpass USD 45 billion by 2030, with a rapidly growing demand for cost-effective, portable, and user-friendly devices.[9] MOF-based biosensors hold strong commercial promise due to their tunable structures and ability to function under ambient conditions.[10] However, current commercial solutions have not fully leveraged MOFs' potential, leaving an opportunity for innovation in scalable, integrated platforms. MOFs, synthesized using organic linkers and metal ions, offer tunable chemical properties that make them highly effective for glucose detection (Fig. 1). The structural porosity and functional groups of MOFs allow selective binding with glucose or other biomarker molecules, enhancing detection efficiency. Recent advancements in MOF-based biosensors have demonstrated remarkable potential in biomedical diagnostics. In our study, we synthesized a novel Fe-doped Zinc-MOF composite (Fe@Zinc-MOF-2) and developed a luminescent probe for highly selective and sensitive glucose detection in both model and real urine samples. The probe exhibited excellent fluorescence quenching properties, achieving detection limits as low as 1.17 ppm and 0.846 ppm for glucose concentrations of 110 mg dL^{-1} and 150 mg dL^{-1}, respectively.[11] Additionally, we fabricated a test strip by integrating Fe@Zinc-MOF-2 composite with filter paper, enabling rapid and visible glucose detection through fluorescence changes under UV light.

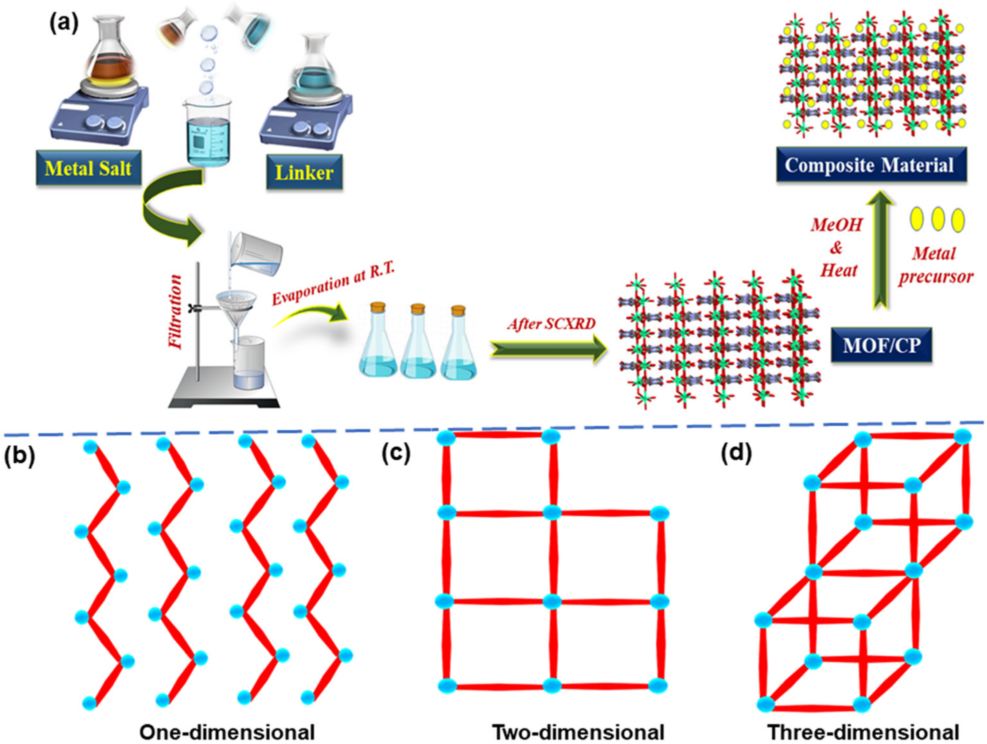
Beyond glucose detection, MOF-based test strips have also been successfully employed for the colorimetric detection of trichloroacetic acid (TCA), a carcinogenic metabolite in human urine. A fluorescein-functionalized Zn-based MOF (FS@Zn-MOF-2) was designed as a microporous luminescent probe, offering a rapid response time of less than 30 seconds and a detection limit of 1.22 ppm. The portable paper-based FS@Zn-MOF-2 strip displayed a distinct fluorescence change upon exposure to TCA, providing an efficient, selective, and user-friendly approach for monitoring TCE exposure.[12] The

Vibhav Shukla

Vibhav Shukla is a dedicated researcher in inorganic chemistry, specializing in the design and application of metal–organic frameworks (MOFs) and coordination polymers (CPs). He completed his B.Sc. and M.Sc. in Chemistry from CSJM University, Kanpur, in 2014 and 2016, respectively, and qualified CSIR-NET JRF (AIR 52), demonstrating academic excellence. Since 2022, he has been a full-time research scholar at National Institute of Technology Raipur, focusing on luminescence sensing, photocatalytic degradation, and energy storage applications, exploring MOFs and their composites for environmental and technological advancements. He has published 12 research papers in reputed international journals and a book chapter with ACS Publications. His expertise includes SCXRD, FTIR, SEM-EDX, Raman spectroscopy, PXRD, and XPS analysis, with a research vision centered on developing innovative materials with enhanced functional properties for real-world applications.

Kafeel Ahmad Siddiqui

Dr. Kafeel Ahmad Siddiqui is an Associate Professor in the Department of Chemistry at the National Institute of Technology (NIT) Raipur, India. With a strong academic and research background, Dr. Siddiqui has made significant contributions to the fields of material science, catalysis, and nanotechnology, focusing particularly on metal–organic frameworks (MOFs) and their applications in environmental sustainability and biomedical diagnostics. Dr. Siddiqui holds a Ph.D. in Chemistry from MNNIT Allahabad, India, and has completed his postdoctoral research at the Indian Institute of Science (IISc) Bangalore. He has extensive experience in synthesizing and characterizing advanced materials and is passionate about applying green chemistry principles to the development of novel materials with real-world applications, including their use in clean energy solutions, sensing technologies, and water purification. Throughout his career, Dr. Siddiqui has published more than 70 research articles in high-impact journals and has been involved in various national and international collaborations. He is actively engaged in mentoring students, guiding them in their research projects, and inspiring the next generation of scientists in the field of chemistry. His current research involves developing MOF-based test strips for real-time, visual detection of glucose and other toxic biomolecules in urine, aiming to advance low-cost, point-of-care diagnostics using green chemistry principles and effect of doping in MOF on energy storage capacity.



Scheme 1 (a) Schematic representation of MOF and composite synthesis, illustrating the stepwise formation process along with examples of (b) 1D, (c) 2D, and (d) 3D MOFs.

performance metrics of selected MOF-based test strips in real samples are summarized in Table 1.

Additionally, MOF-based test strips have been developed for uric acid detection, which is crucial for diagnosing hyperuricemia and related metabolic disorders. A phosphonate MOF composite (Cu^{2+}@MIL-91(Al:Eu)) exhibited an "off–on" fluorescence mechanism upon interaction with uric acid, achieving a detection limit as low as 1.6 μM. The MOF-integrated test strip demonstrated high selectivity in real urine samples, enabling rapid, cost-effective, and accurate diagnosis of abnormal uric acid levels.[23]

Beyond laboratory demonstrations, MOF-based biosensors have also shown practical applicability in real clinical and

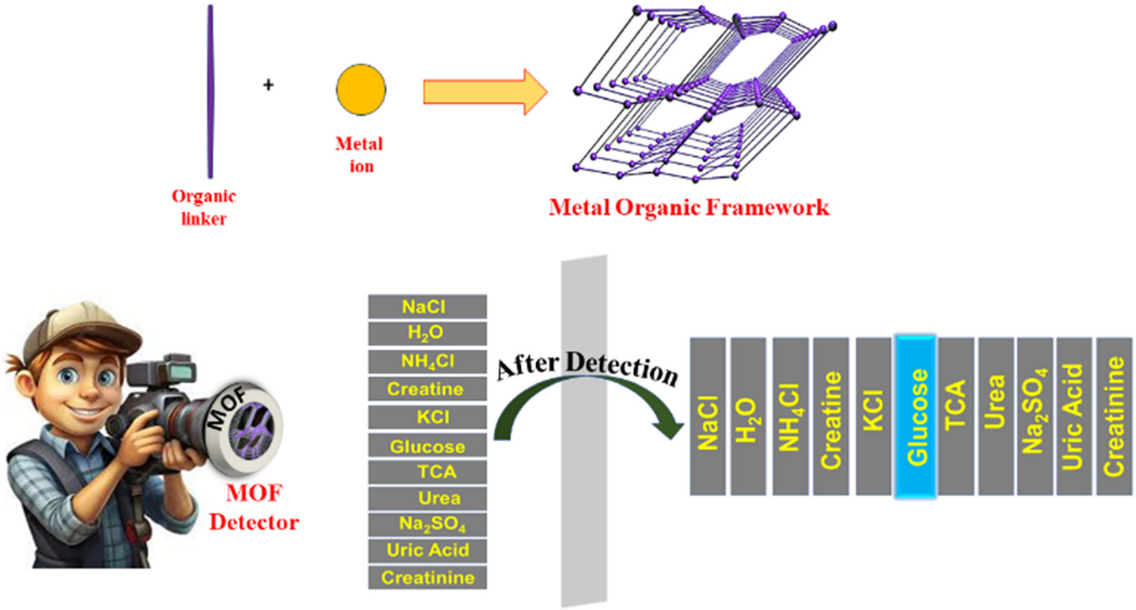


Fig. 1 Schematic illustration of MOF synthesis using organic linkers and metal ions, followed by its application as a detector for glucose sensing in urine constituents.

Table 1 Comparative analysis of MOFs, MXenes, and borophene for biosensor applications

S. no	Feature	MOFs	MXenes	Borophene	Ref.
1	Conductivity	Moderate	High	Very high	13, 14
2	Stability	High (with modification)	Low (oxidation prone)	Very low (unstable in ambient)	15, 16
3	Surface functionalization	Easy	Moderate	Difficult	17, 18
4	Eco-friendliness	High	Moderate	Low	19, 20
5	Biosensing versatility	High	Medium	Medium	21, 22

environmental scenarios.[24] For instance, Fe@Zinc-MOF-2 integrated test strips have been successfully applied to detect glucose concentrations directly from human urine samples, demonstrating high selectivity and rapid response times. In infectious disease diagnostics, MOF-derived fluorescent sensors have been used for the detection of SARS-CoV-2 RNA during the COVID-19 pandemic, showcasing high sensitivity and short assay times suitable for point-of-care testing.[25] Similarly, FS@Zn-MOF-based portable strips have efficiently detected trichloroacetic acid (TCA), a carcinogenic environmental metabolite, in real urine samples, enabling early exposure monitoring in occupational settings. Additionally, phosphonate MOF composites such as Cu^{2+}@MIL-91(Al:Eu) have enabled uric acid quantification in real clinical samples, facilitating the diagnosis of hyperuricemia and related metabolic disorders. These case studies underscore the translational potential of MOF-based biosensors, moving beyond proof-of-concept experiments toward practical healthcare and environmental monitoring solutions.

MOFs offer several advantages that can overcome the limitations of traditional test strips:

- Increased detection efficiency: MOFs can be tailored to selectively interact with target analytes, enhancing the ability to detect even trace amounts with exceptional precision.[26]
- Environmentally friendly fabrication: MOFs are often created through sustainable processes that minimize the environmental footprint of production.[27]
- Multi-analyte detection: MOFs' flexibility allows for the design of test strips that can simultaneously identify several different analytes, enhancing diagnostic efficiency.[28]

Since MOFs can be made from readily available, inexpensive materials, they help reduce the environmental impact and cost of producing test strips. The development of Fe@Zinc-MOF-2, FS@Zn-MOF, and Cu^{2+}@MIL-91(Al:Eu)-based test strips highlights the transformative role of MOF composites in next-generation biomedical diagnostics, paving the way for more sensitive, reliable, and eco-friendly healthcare solutions.

3. Expanding the scope of MOF-enhanced test strips

The continuous evolution of biomedical diagnostics has driven the need for more precise, rapid, and cost-effective sensing technologies. Metal–organic frameworks (MOFs) have emerged as transformative materials in this field due to their tunable porosity,[29] high surface area,[30] and versatile functionalization capabilities.[31] Their ability to interact with analytes *via* multiple detection mechanisms—such as electrochemical, fluorescence, and colorimetric methods—makes them ideal candidates for diagnostic test strips.[32,33] Unlike conventional test strips, which often suffer from stability limitations and lower sensitivity, MOF-enhanced test strips provide improved detection performance and durability. Recent advancements have demonstrated their effectiveness in detecting glucose, infectious diseases, disease biomarkers, heavy metals, and metabolic waste products in biological fluids, paving the way for their widespread adoption in clinical and environmental monitoring applications.

Comparison with other emerging materials: MXenes, borophene, and beyond

Alongside MOFs, other next-generation materials such as MXenes and borophene have been explored for biosensor applications due to their outstanding electrical conductivity and mechanical strength.[34] MXenes, known for their hydrophilic surfaces and high electron mobility, offer efficient electrochemical sensing.[35] However, they suffer from oxidation issues and have relatively limited surface functionalization compared to MOFs, reducing their versatility for selective biomarker detection. Similarly, borophene, with its exceptional carrier mobility, faces significant challenges related to environmental instability and scalable production.[36] In contrast, MOFs stand out due to their modular design, enabling fine control over pore size, chemical functionality, and biocompatibility.[37] This unique tunability allows MOFs to support multiple sensing modalities (*e.g.*, fluorescence, colorimetric, electrochemical) within a single material platform. Furthermore, their structural robustness under mild biological conditions makes them more suitable for developing reliable, sustainable, and high-performance biomedical test strips. Thus, while MXenes and borophene present exciting prospects, MOFs offer a comprehensive and adaptable framework tailored for advanced diagnostic applications.

Furthermore, in the context of 5th generation biosensors—such as wearable devices, breath-based diagnostics, and integrated AI platforms—MOFs present unique advantages over MXenes and borophene.[38,39] Although MXenes exhibit excellent electrical conductivity suitable for electrochemical biosensors and borophene offers exceptional mechanical strength, their widespread application is hindered by issues like environmental instability, oxidative degradation, and difficulties in surface functionalization.[40] Breath-based diagnostics, for instance, demand materials that can operate reliably in humid and complex biological environments. MOFs, with their superior chemical tunability, high porosity, and intrinsic luminescent properties, enable selective and sensitive detection of volatile biomarkers such as nitric oxide, acetone, and ammonia in exhaled breath.[41] Additionally, MOFs can be engineered to exhibit dual functionalities (*e.g.*, optical and electrochemical responsiveness), crucial for the development of multifunctional "nose-on-chip" devices.[42]

Recent advances have demonstrated that MOF-based chips can detect trace biomarkers in breath with high sensitivity and stability, making them ideal candidates for next-generation wearable diagnostics and portable breath analysers. While MXenes and borophene show promise, the modular architecture of MOFs allows for precise pore tailoring and surface chemistry adaptation, providing a more versatile and biocompatible platform for integrated biosensing applications. Therefore, our focused emphasis on MOF chips stems from their superior versatility, environmental stability, multifunctionality, and proven translational potential in real-world 5th-generation diagnostic technologies. A comparative summary of various MOF-based biosensing systems, their performance parameters, and real-sample applicability is presented in Table 2, illustrating the practical potential and versatility of MOF-integrated diagnostics.

Glucose detection. MOF-enhanced test strips have been developed for glucose monitoring, where MOFs are functionalized to selectively bind glucose with high affinity, offering faster and more sensitive detection than traditional enzyme-based methods.

- Infectious disease diagnostics: MOFs can be engineered to target specific pathogens or biomarkers linked to diseases like malaria, tuberculosis, or COVID-19. By incorporating MOFs with customized binding sites, test strips can deliver quicker, more accurate results for disease detection.
- Disease biomarker identification: MOFs can be designed to selectively bind disease biomarkers, enabling test strips to detect low concentrations of specific proteins or genetic material, improving diagnostic sensitivity.
- Heavy metal detection: MOFs can be tailored to identify trace amounts of heavy metals in biological fluids, providing an efficient and sensitive alternative to traditional chemical detection methods.

Glucose monitoring plays a vital role in managing diabetes and other metabolic disorders.[46] Unlike conventional enzyme-based glucose test strips, which suffer from stability issues and limited sensitivity, MOF-based alternatives provide higher selectivity and durability (Fig. 2). The direct electron transfer properties of MOFs eliminate the need for enzymatic components, making them more reliable for long-term use. Traditional enzyme-based glucose sensors, which primarily depend on glucose oxidase, often face stability issues due to enzyme degradation. In contrast, MOF-based glucose sensors provide enzyme-free, highly sensitive, and selective detection methods.[47] These sensors, when combined with conductive materials such as carbon nanomaterials, metal nanoparticles, and metal oxides, have demonstrated excellent performance in electrochemical glucose detection. Among them, copper-based MOFs are widely used due to their strong redox activity, and their combination with gold nanoparticles enhances electron transfer efficiency, leading to improved glucose sensing in biological samples. Similarly, cobalt-based MOFs exhibit peroxidase-like activity, allowing for enzyme-free glucose detection through oxidation reactions. Researchers have also developed MOF-based glucose sensors anchored on nanomaterials like graphene oxide, which offer high sensitivity and selectivity for detecting glucose in different biological fluids.[48]

Apart from electrochemical detection, luminescent MOFs have been utilized for fluorescence-based glucose sensing. Certain lanthanide-based MOFs exhibit fluorescence changes upon interaction with glucose, enabling a rapid and label-free sensing approach.[49] Other MOFs, integrated with quantum dots, have demonstrated ultra-sensitive glucose detection, reaching nanomolar detection limits. In addition, colorimetric glucose sensors based on MOFs mimic natural enzyme activity, producing visible colour changes when reacting with glucose. This allows for simple and effective glucose detection without requiring complex instrumentation.

Beyond glucose monitoring, MOFs have been extensively explored for identifying disease biomarkers, which is crucial for early disease detection and prognosis. These materials

Table 2 Comparative performance of various MOF-based biosensing systems for real-world diagnostic applications

MOF-based system	Target analyte	Detection method	Detection limit	Response time	Real sample used	Ref.
Fe@Zn-MOF-2	Glucose	Fluorescence quenching	0.846 ppm	~5 sec	Human urine	11
FS@Zn-MOF	Trichloro acetic acid (TCA)	Colorimetric (fluorescein)	1.22 ppm	<30 sec	Urine (occupational)	43
Cu^{2+}@MIL-91(Al:Eu)	Uric acid	"Off–on" fluorescence	1.6 μM	Fast	Clinical urine	44
Zr-MOF@GO	Dopamine	Electrochemical	50 nM	Seconds	Serum	19
Co-MOF/AuNPs	Glucose	Enzyme-free electrochemical	0.16 μM	Few sec	Saliva	45
Tb-MOF/quantum dots	Glucose	Fluorescence ratiometric	10 nM	<1 min	Buffer	19
MOF-74(Ni)/CNT	H_2O_2 (indirect glucose)	Amperometric	1.2 μM	Fast	Serum	45
Eu-MOF	SARS-CoV-2 RNA	Fluorescence (hybridization)	87 copies per mL	~20 min	Nasopharyngeal swab	19
MIL-101(Fe)/aptamer	Aflatoxin B1 (food toxin)	Electrochemical	0.09 ng mL^{-1}	Few min	Corn & peanut extract	17
ZIF-8@PDA@PtNPs	Glucose	Colorimetric + catalytic	1.1 μM	<5 min	Blood plasma	45

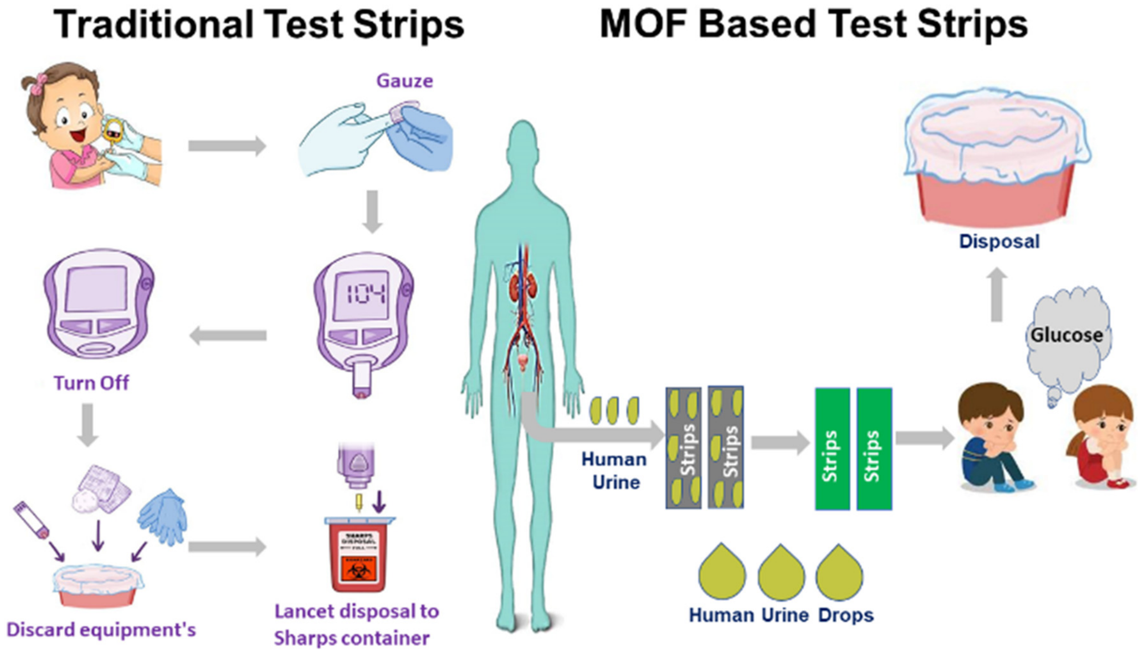


Fig. 2 Comparison between traditional test strips and MOF-based test strips for glucose detection. The MOF-based approach simplifies the process, reducing waste and offering an eco-friendly alternative to conventional methods.

have been functionalized with various biological recognition elements, such as antibodies, aptamers, and DNA probes, to detect biomarkers associated with different diseases.[50] For instance, MOF-based biosensors have been used for detecting cancer biomarkers at extremely low concentrations, making them promising tools for early cancer diagnosis. Some MOF sensors have also been developed for detecting microRNAs linked to certain cancers, offering high selectivity and efficiency in diagnostic applications. MOFs have further shown potential in diagnosing bacterial and viral infections by detecting specific proteins or nucleic acids. During the COVID-19 pandemic, MOF-based fluorescence sensors were employed for the rapid detection of viral RNA, demonstrating high sensitivity. Additionally, electrochemical MOF-based immunosensors have been developed for detecting tuberculosis biomarkers, offering accurate and reliable results.

In neurodegenerative disease diagnostics, MOFs have been applied to detect biomarkers related to conditions such as Alzheimer's and Parkinson's diseases. Some MOF-based sensors have been designed to detect amyloid-β aggregates, which are linked to Alzheimer's, enabling early-stage diagnosis. Similarly, MOF-based biosensors have been used for dopamine detection, playing a significant role in diagnosing Parkinson's disease by providing rapid and selective detection. MOF-based biosensors are transforming the landscape of biomedical diagnostics by offering high sensitivity, selectivity, and rapid detection capabilities. Their adaptability to various detection techniques, including electrochemical, fluorescence, and colorimetric methods, makes them highly promising for next-generation healthcare applications. Ongoing research continues to focus on enhancing their stability, scalability, and real-world clinical applicability, ensuring their integration into practical diagnostic tools in the near future.

4. Environmental and economic impact

The incorporation of MOFs into as biomedical test strips is well-aligned with the growing need for sustainable and affordable healthcare solutions.[51] Traditional diagnostic tests often rely on harmful chemicals, materials, or processes that contribute to environmental degradation. In contrast, MOFs can be synthesized using more eco-friendly methods, minimizing the reliance on toxic solvents and reagents, which significantly reduces environmental pollution. Furthermore, the high stability and recyclability of MOFs could lead to a reduction in medical waste, particularly in point-of-care diagnostic applications, where frequent use of disposable materials is common.

From an economic perspective, MOF-based test strips offer significant cost advantages. The raw materials used to synthesize MOFs are often abundant and inexpensive, and the scalable nature of MOF production further reduces manufacturing costs. Additionally, the cost-effective synthesis of MOFs supports scalable production, making these test strips accessible for large-scale healthcare applications (Fig. 3). Their long lifespan and reusability further contribute to cost savings and reduced medical waste. This economic efficiency has the potential to make diagnostic tools more affordable, particularly in resource-limited regions, thereby enhancing access to essential healthcare services. Additionally, the long lifespan and reusability of MOFs may decrease the need for frequent

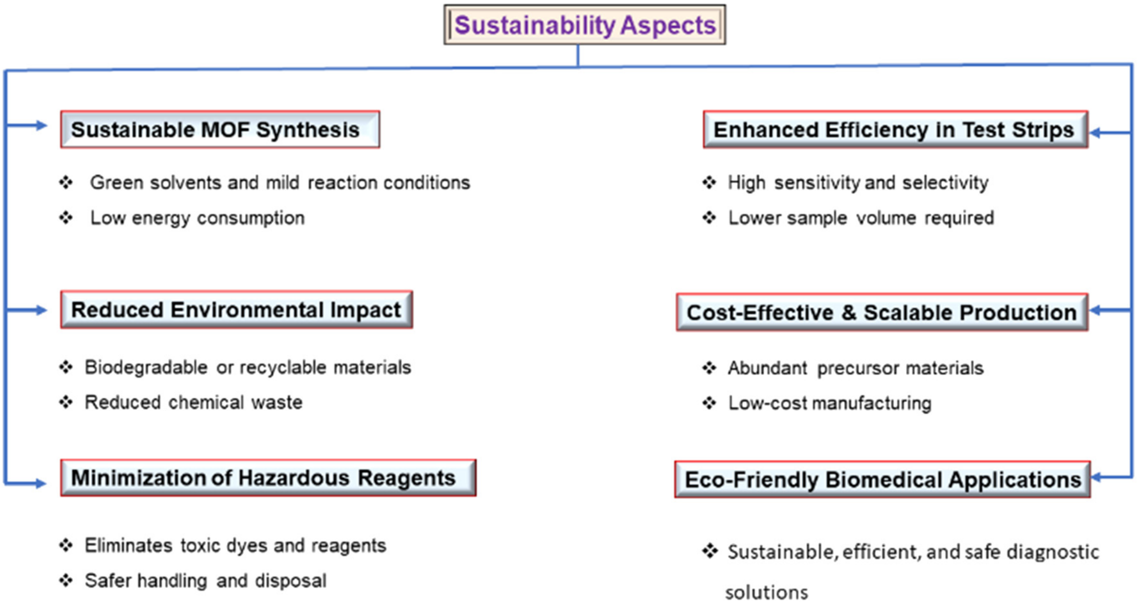


Fig. 3 Sustainability aspects of MOF-based test strips, emphasizing their eco-friendly and efficient characteristics.

replacement of diagnostic equipment, leading to cost savings over time.

Further potential benefits

- Reduced healthcare costs: by creating more cost-effective diagnostic tools, MOFs can lower the overall cost of healthcare, especially in regions with limited resources.
- Sustainable production: MOFs' ability to be synthesized from renewable materials supports the shift toward a circular economy, reducing the overall environmental footprint of the healthcare industry.
- Scalable manufacturing: the ease with which MOFs can be produced at scale may enable rapid deployment of affordable, high-quality diagnostic tools worldwide, helping bridge gaps in healthcare accessibility.

In summary, MOFs not only offer a more environmentally sustainable approach to diagnostic technology but also present an opportunity for reducing costs and improving healthcare access, particularly in underserved communities.

5. Challenges and future directions

Despite the promising advantages of MOFs in biomedical diagnostics, several challenges remain that must be addressed before their widespread commercial adoption. These challenges include issues related to large-scale production, environmental stability, regulatory hurdles, and real-world clinical implementation. Addressing these concerns through ongoing research and technological advancements will be critical in realizing the full potential of MOF-based test strips.

Challenges in MOF-based test strip development

- Scalability and manufacturing costs: while MOFs exhibit excellent sensing capabilities, their large-scale production remains a major bottleneck. Traditional synthesis methods, such as solvothermal and hydrothermal approaches, are often time-consuming and require precise conditions to maintain uniformity. Additionally, the use of expensive precursors and complex fabrication techniques increases production costs, making MOF-based test strips less commercially viable than conventional diagnostic materials. Developing scalable and cost-effective manufacturing techniques, such as mechanochemical synthesis, microwave-assisted synthesis, or green solvent-based methods, is crucial for their broader adoption.
- Stability under real-world conditions: MOFs can be sensitive to environmental factors such as humidity, temperature fluctuations, and exposure to air, which can lead to structural degradation over time. In biomedical applications, test strips must maintain their functionality across diverse climates, including high-humidity regions where moisture absorption could alter the MOF's properties. Researchers are actively working on developing more robust MOFs with enhanced water stability by modifying their organic linkers, incorporating hydrophobic coatings, or designing hybrid composite materials to improve durability in real-world conditions.
- Regulatory and safety concerns: the introduction of any new medical diagnostic technology requires extensive validation, regulatory approvals, and clinical trials to ensure safety and efficacy. Regulatory agencies such as the Food and Drug Administration (FDA) and the European Medicines Agency (EMA) require rigorous testing before MOF-based biosensors can be integrated into mainstream healthcare. MOFs containing metal ions raise concerns about biocompatibility and potential

toxicity, necessitating further studies to assess their long-term effects on human health. Developing bio-safe, non-toxic MOF formulations and demonstrating their reliability in real-world clinical studies will be key to gaining regulatory approval.

- Reproducibility and standardization: the performance of MOF-based test strips can vary due to differences in synthesis conditions, batch-to-batch inconsistencies, and challenges in quality control. Unlike traditional enzyme-based biosensors, which have well-defined production parameters, MOFs' diverse structural possibilities introduce complexities in ensuring uniformity across large-scale production. Establishing standardized fabrication protocols and improving quality control mechanisms are essential to overcoming this challenge.

5.1 Socio-economic and interdisciplinary perspectives

While technical and manufacturing challenges remain significant for MOF-based diagnostic devices, socio-economic factors also play a critical role in their practical adoption. Although MOF-enabled biosensors offer enhanced sensitivity and cost-effective synthesis routes, barriers such as affordability for low-income populations, accessibility in rural or underserved regions, and public trust in new diagnostic technologies must be addressed.[52]

Large-scale deployment of MOF-based test strips requires the establishment of affordable manufacturing pipelines, education of healthcare providers, and public engagement campaigns to build awareness about the advantages of these new technologies. Interdisciplinary collaboration between material scientists, healthcare professionals, social scientists, and communication experts will be essential to promote user adoption and societal acceptance. From a research standpoint, there remains a significant gap in transitioning MOF-based sensing systems from laboratory prototypes to clinically viable, scalable test strips. Most published work focuses on fundamental sensor development without demonstrating applicability in real-world samples or addressing regulatory scalability.[53] Our study bridges this gap by successfully applying Fe@Zn-MOF test strips for glucose detection in actual urine samples and by exploring fabrication compatibility with paper substrates for low-cost deployment.[8]

Initiatives such as using visual arts, community outreach programs, and policy advocacy, as demonstrated in interdisciplinary approaches to pandemics like monkeypox prevention, can serve as models for the promotion of MOF-based diagnostics. Future research should integrate socio-economic impact studies, market access strategies, and public health communication to ensure that the technological advancements in MOFs translate into real-world healthcare benefits globally.[54]

5.2 Future research directions and innovations

To overcome these challenges, research efforts should focus on the following key areas:

- Enhancing stability and durability: researchers are exploring ways to improve the water and thermal stability of MOFs by incorporating protective coatings, hydrophobic functional groups, and hybrid composites with polymers or metal nanoparticles. Future studies should aim to develop next-generation MOFs with increased resistance to environmental factors, ensuring their longevity in real-world diagnostic applications.

- Developing low-cost, scalable synthesis techniques: advancements in solvent-free mechanochemical synthesis, microwave-assisted fabrication, and 3D printing of MOF-based test strips could significantly reduce costs and enhance scalability. Sustainable synthesis approaches that eliminate toxic solvents and use renewable materials will also contribute to making MOFs more commercially feasible.

- Integration with smart and wearable technologies: the future of biomedical diagnostics lies in smart and wearable biosensors. MOF-based materials, when integrated with flexible electronics, smartphone-based readout systems, and AI-driven diagnostic platforms, could revolutionize real-time health monitoring. Research should focus on adapting MOFs for continuous, on-the-go monitoring in wearable sensor formats.

- Integration of MOFs with AI, wearable devices, and smartphone diagnostics: the next generation of healthcare diagnostics is expected to be highly personalized, real-time, and decentralized, driven by smart technologies. Artificial Intelligence (AI) can significantly enhance the performance of MOF-based biosensors by enabling automated pattern recognition, predictive diagnostics, and anomaly detection based on complex biosensing data.[55] Machine learning algorithms can be trained to interpret subtle fluorescence, colorimetric, or electrochemical signals from MOF-based test strips, improving diagnostic accuracy and reducing human error. In addition to AI, wearable biosensors incorporating MOF composites offer promising solutions for continuous health monitoring. Flexible and stretchable electronics embedded with MOFs can detect biomarkers in sweat, saliva, or interstitial fluids, allowing for non-invasive and real-time monitoring of chronic diseases like diabetes and cardiovascular conditions. Wearable patches, wristbands, and even textiles functionalized with MOF-based sensors are emerging as potential platforms for next-generation diagnostics.

Furthermore, smartphone-based detection systems integrated with MOF test strips are gaining traction due to their portability, affordability, and ease of use. Smartphone cameras, combined with app-based analytical tools, can be employed to read color changes, fluorescence emissions, or electrochemical signals from MOF-enhanced strips, providing immediate diagnostic feedback even in resource-limited settings. This integration opens up the possibility of widespread adoption of point-of-care diagnostics, telemedicine support, and remote patient monitoring, ultimately contributing to more proactive and accessible healthcare management.

- Broadening biomedical and environmental applications: while MOFs have already demonstrated success in glucose sensing and disease biomarker detection, expanding their use in cancer diagnostics, hormone-level monitoring, early-stage infection detection, and environmental pollutant analysis can greatly enhance their impact. Additionally, MOF-based test strips could be employed for real-time monitoring of airborne toxins, food contaminants, and water quality to improve public health monitoring.

With these advancements, MOFs could pave the way for the next generation of diagnostic tools, making them more for a wide range of medical and environmental applications. By addressing the current challenges and leveraging innovative technologies, MOF-based test strips have the potential to transform healthcare diagnostics and contribute to more efficient, accurate, and sustainable point-of-care testing.

Looking ahead, MOF-based biosensors are expected to play a transformative role in the global diagnostics market, which is projected to surpass USD 45 billion by 2030, with significant growth in point-of-care and wearable diagnostics. Within the next 5–7 years, the integration of MOFs with AI-driven smartphone applications and flexible wearable platforms is anticipated to transition from laboratory prototypes to commercial healthcare products. Advances in real-time breath-based MOF sensors could lead to non-invasive disease diagnostics for respiratory disorders, metabolic syndromes, and even early cancer detection. Moreover, regulatory progress and the establishment of clinical testing pipelines may enable the first MOF-based diagnostic strips to enter the FDA approval process within the decade. These emerging trends suggest a clear trajectory where MOFs will underpin next-generation biosensing technologies tailored for personalized, on-demand, and decentralized healthcare.

6. Conclusion and future prospects

The integration of metal–organic frameworks (MOFs) into biomedical test strips presents a significant advancement in healthcare diagnostics, offering sustainable and highly efficient solutions for a range of applications, including glucose monitoring and pathogen detection. These innovative materials not only enhance existing diagnostic methodologies but also enable the development of novel tools capable of detecting a broad spectrum of health-related biomarkers. Furthermore, their environmentally friendly properties and potential for scalable manufacturing contribute to a more sustainable and accessible healthcare system.

As research continues to refine MOF synthesis, improve stability, and expand biomedical applications, the adoption of MOF-integrated technologies in diagnostics is expected to increase. However, addressing regulatory challenges and optimizing production efficiency will be crucial in facilitating their widespread implementation in the global market. Ultimately, MOFs hold immense promise for revolutionizing diagnostic capabilities, providing a cost-effective, sustainable, and highly sensitive approach to disease detection and monitoring. With continued advancements in material science and biomedical engineering, MOF-based diagnostics may pave the way for more personalized, portable, and real-time healthcare solutions. Collaborative efforts among researchers, clinicians, and industry stakeholders will be key to unlocking their full potential in revolutionizing global healthcare.

Data availability

No experimental data were used in the manuscript.

Conflicts of interest

There are no conflicts to declare.

Notes and references

1 L. V. Jones, A. Ray, F. M. Moy and B. S. Buckley, *Cochrane Database Syst. Rev.*, 2019, **5**, CD009613.
2 D. Mukherjee, A. Pal, S. C. Pal, A. Saha and M. C. Das, *Inorg. Chem.*, 2022, **61**, 16952–16962.
3 Z. Gan, X. Hu, X. Xu, W. Zhang, X. Zou, J. Shi, K. Zheng and M. Arslan, *Food Chem.*, 2021, **354**, 129501.
4 (*a*) V. Shukla, M. Ahmad, G. C. Nayak, T. S. Thakur and K. A. Siddiqui, *Cryst. Growth Des.*, 2024, **24**, 3977–3992; (*b*) V. Shukla and K. A. Siddiqui, in *ACS Symposium Series*, American Chemical Society, Washington, DC, 2024, pp. 223–245.
5 (*a*) D. Mukherjee, A. Pal, S. C. Pal, A. Saha and M. C. Das, *Inorg. Chem.*, 2022, **61**, 16952–16962; (*b*) Z. Gan, X. Hu, X. Xu, W. Zhang, X. Zou, J. Shi, K. Zheng and M. Arslan, *Food Chem.*, 2021, **354**, 129501.
6 Y. Luo, Y. Sun, H. Wang, Y. He, M. Lu, R. Wang and D. Xu, *CrystEngComm*, 2025, **27**, 1262–1270.
7 J. F. Olorunyomi, S. T. Geh, R. A. Caruso and C. M. Doherty, *Mater. Horiz.*, 2021, **8**, 2387–2419.
8 Z. Jin, W. Yim, M. Retout, E. Housel, W. Zhong, J. Zhou, M. S. Strano and J. V. Jokerst, *Chem. Soc. Rev.*, 2024, **53**, 7681–7741.
9 Point of care diagnostics market growth, drivers, and opportunities, **https://www.marketsandmarkets.com/Market-Reports/point-of-care-diagnostic-market-106829185.html**, (accessed May 2, 2025).
10 (*a*) A Review: Metal-Organic Frameworks Electrochemical Biosensors for Bioorganic Materials Detection, 2024, DOI: **10.22034/abec.2024.710597**; (*b*) M. K. Muthukumaran, M. Govindaraj, S. Kogularasu, B. Sriram, B. K. Raja, S.-F. Wang, G.-P. Chang-Chien and A. Selvi J, *Talanta Open*, 2025, **11**, 100396.
11 V. Shukla, M. Ahmad and K. A. Siddiqui, *Mater. Today Chem.*, 2024, **38**, 102138.
12 B.-H. Wang and B. Yan, *CrystEngComm*, 2019, **21**, 4637–4643.
13 L. Xu, X. Zhang, Z. Wang, A. A. Haidry, Z. Yao, E. Haque, Y. Wang, G. Li, T. Daeneke, C. F. McConville, K. Kalantar-Zadeh and A. Zavabeti, *Nanoscale*, 2021, **13**, 11017–11040.
14 (*a*) M. Alikhani, S. Hajibaba, M. Moayedi and Y. Abdi, *J. Energy Storage*, 2024, **99**, 113301; (*b*) R. Saha and C. J. Gómez García, *Chem. Soc. Rev.*, 2024, **53**, 9490–9559.

15 J. Dong, D. Zhao, Y. Lu and W.-Y. Sun, *J. Mater. Chem. A*, 2019, **7**, 22744–22767.

16 (*a*) H. Huang, W. Feng and Y. Chen, *Chem. Soc. Rev.*, 2021, **50**, 11381–11485; (*b*) P. Kumar, G. Singh, R. Bahadur, Z. Li, X. Zhang, C. I. Sathish, M. R. Benzigar, T. Kim Anh Tran, N. T. Padmanabhan, S. Radhakrishnan, J. C. Janardhanan, C. Ann Biji, A. Jini Mathews, H. John, E. Tavakkoli, R. Murugavel, S. Roy, P. M. Ajayan and A. Vinu, *Prog. Mater. Sci.*, 2024, **146**, 101331.

17 Y. Zhao, H. Zeng, X.-W. Zhu, W. Lu and D. Li, *Chem. Soc. Rev.*, 2021, **50**, 4484–4513.

18 (*a*) R. E. Ustad, S. S. Kundale, K. A. Rokade, S. L. Patil, V. D. Chavan, K. D. Kadam, H. S. Patil, S. P. Patil, R. K. Kamat, D.-K. Kim and T. D. Dongale, *Nanoscale*, 2023, **15**, 9891–9926; (*b*) S. Yadav, M. A. Sadique, A. Kaushik, P. Ranjan, R. Khan and A. K. Srivastava, *J. Mater. Chem. B*, 2022, **10**, 1146–1175.

19 H. H. Do, J. H. Cho, S. M. Han, S. H. Ahn and S. Y. Kim, *Sensors*, 2021, **21**, 7423.

20 (*a*) B. Farasati Far, N. Rabiee and S. Iravani, *RSC Adv.*, 2023, **13**, 34562–34575; (*b*) S. Ajmal, J. Huang, M. Singh, A. Kumar, J. Guo, M. Tabish, M. A. Mushtaq, M. M. Alam, X. Song and G. Yasin, *Small*, 2025, **21**, e2411311.

21 C. Li, A. K. Tareen, K. Khan, J. Long, I. Hussain, M. F. Khan, M. Iqbal, Z. Xie, Y. Zhang, A. Mahmood, N. Mahmood, W. Ahmad and H. Zhang, *Prog. Solid State Chem.*, 2023, **70**, 100392.

22 (*a*) A. Khunger, N. Kaur, Y. K. Mishra, G. Ram Chaudhary and A. Kaushik, *Mater. Lett.*, 2021, **304**, 130656; (*b*) V. Chaudhary, A. Kaushik, H. Furukawa and A. Khosla, *ECS Sens. Plus*, 2022, **1**, 013601.

23 X. Lian and B. Yan, *Inorg. Chem.*, 2017, **56**, 6802–6808.

24 B. Mohanty, S. Kumari, P. Yadav, P. Kanoo and A. Chakraborty, *Coord. Chem. Rev.*, 2024, **519**, 216102.

25 (*a*) A. Elgazar, R. Sabouni, M. Ghommem and A. F. Majdalawieh, *Sci. Rep.*, 2025, **15**, 1132; (*b*) C. Zhou, C. Lin, Y. Hu, H. Zan, X. Xu, C. Sun, H. Zou and Y. Li, *Lebenson. Wiss. Technol.*, 2022, **169**, 114032.

26 Y. Shi, Y. Zou, M. S. Khan, M. Zhang, J. Yan, X. Zheng, W. Wang and Z. Xie, *J. Mater. Chem. C*, 2023, **11**, 3692–3709.

27 K. Boukayouht, L. Bazzi and S. El Hankari, *Coord. Chem. Rev.*, 2023, **478**, 214986.

28 H. Meskher, S. B. Belhaouari and F. Sharifianjazi, *Heliyon*, 2023, **9**, e21621.

29 V. Shukla, M. Ahmad, G. C. Nayak, T. S. Thakur and K. A. Siddiqui, *Cryst. Growth Des.*, 2024, **24**, 3977–3992.

30 P. Sharma, M. Ahmad, N. Haq and K. A. Siddiqui, *CrystEngComm*, 2024, **26**, 6472–6485.

31 M. Kukreja, M. Ahmad, Somnath and K. A. Siddiqui, *Inorg. Chim. Acta*, 2024, **572**, 122274.

32 J. Hu, S. Chen, Z. Liu, J.-R. Li, J.-H. Huang, Z. Jiang, W. Ou, W.-M. Liao, J. Lu and J. He, *J. Mater. Chem. A*, 2023, **11**, 10577–10583.

33 V. Shukla, G. Aalam, S. W. Ali, M. Ahamd, N. Haq and K. A. Siddiqui, *New J. Chem.*, 2025, **49**, 1648–1662.

34 C. Li, A. K. Tareen, K. Khan, J. Long, I. Hussain, M. F. Khan, M. Iqbal, Z. Xie, Y. Zhang, A. Mahmood, N. Mahmood, W. Ahmad and H. Zhang, *Prog. Solid State Chem.*, 2023, **70**, 100392.

35 N. Sarma, H. Das and P. Saikia, *ACS Sens.*, 2025, **10**, 622–641.

36 D. Li, A. Yadav, H. Zhou, K. Roy, P. Thanasekaran and C. Lee, *Glob Chall.*, 2024, **8**, 2300244.

37 V. F. Yusuf, N. I. Malek and S. K. Kailasa, *ACS Omega*, 2022, **7**, 44507–44531.

38 V. Chaudhary, V. Khanna, H. T. Ahmed Awan, K. Singh, M. Khalid, Y. K. Mishra, S. Bhansali, C.-Z. Li and A. Kaushik, *Biosens. Bioelectron.*, 2023, **220**, 114847.

39 S. Suganthi, K. Ahmad and T. H. Oh, *Molecules*, 2024, **29**(22), 5373.

40 M. Khazaei, A. Mishra, N. S. Venkataramanan, A. K. Singh and S. Yunoki, *Curr. Opin. Solid State Mater. Sci.*, 2019, **23**, 164–178.

41 P. Hajivand, J. Carolus Jansen, E. Pardo, D. Armentano, T. F. Mastropietro and A. Azadmehr, *Coord. Chem. Rev.*, 2024, **501**, 215558.

42 P. Qin, S. Okur, Y. Jiang and L. Heinke, *J. Mater. Chem. A*, 2022, **10**, 25347–25355.

43 B.-H. Wang and B. Yan, *CrystEngComm*, 2019, **21**, 4637–4643.

44 X. Lian and B. Yan, *Inorg. Chem.*, 2017, **56**, 6802–6808.

45 D. B. Gorle, S. Ponnada, M. S. Kiai, K. K. Nair, A. Nowduri, H. C. Swart, E. H. Ang and K. K. Nanda, *J. Mater. Chem. B*, 2021, **9**, 7927–7954.

46 L. Xu, X. Zhang, Z. Wang, A. A. Haidry, Z. Yao, E. Haque, Y. Wang, G. Li, T. Daeneke, C. F. McConville, K. Kalantar-Zadeh and A. Zavabeti, *Nanoscale*, 2021, **13**, 11017–11040.

47 J. Dong, D. Zhao, Y. Lu and W.-Y. Sun, *J. Mater. Chem. A*, 2019, **7**, 22744–22767.

48 D. B. Gorle, S. Ponnada, M. S. Kiai, K. K. Nair, A. Nowduri, H. C. Swart, E. H. Ang and K. K. Nanda, *J. Mater. Chem. B*, 2021, **9**, 7927–7954.

49 H. H. Do, J. H. Cho, S. M. Han, S. H. Ahn and S. Y. Kim, *Sensors*, 2021, **21**, 7423.

50 Y. Zhao, H. Zeng, X.-W. Zhu, W. Lu and D. Li, *Chem. Soc. Rev.*, 2021, **50**, 4484–4513.

51 P. Chakraborty, A. Rana, S. Mukherjee and S. Biswas, *Inorg. Chem.*, 2023, **62**, 802–809.

52 (*a*) O. Oyedeji, O. B. Daramola, O. G. Abimbola, I. V. Daramola and O. R. Ademakinwa, in *Emerging Contaminants in Food and Food Products*, CRC Press, Boca Raton, 2024, pp. 186–215; (*b*) J. Huang, J. Pan, Y. Song, Q. Lin, Y. Xu, Z. Dai and S.-Y. Liu, *TrAC, Trends Anal. Chem.*, 2024, **173**, 117619.

53 (*a*) F. E. Ogulewe, A. A. Oladipo and M. Gazi, *Talanta Open*, 2025, 100448; (*b*) L. d'Amone, G. Matzeu, A. Quijano-Rubio, G. P. Callahan, B. Napier, D. Baker and F. G. Omenetto, *Adv. Mater.*, 2023, **35**, e2208556; (*c*) W. Huang, Q. Ding, H. Wang, Z. Wu, Y. Luo, W. Shi, L. Yang, Y. Liang, C. Liu and J. Wu, *Nat. Commun.*, 2023, **14**, 5221.

54 A. Zuliani, N. Khiar and C. Carrillo-Carrión, *Anal. Bioanal. Chem.*, 2023, **415**, 2005–2023.

55 (*a*) N. Rabiee, *TrAC, Trends Anal. Chem.*, 2025, **184**, 118156; (*b*) J. Cao, L. Zhou, F. Gan and Z. You, *JOM*, 2025, **77**, 1452–1465.