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# Applications of metal organic frameworks in point of care testing

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ABSTRACT

Diagnostic devices used in the point-of-care (POC) today play a critical role as tools to provide essential medical surveillance data and to ensure that patients receive appropriate and timely care. These devices also allow self-analysis by the patient, increasing therapeutic adherence as well as reducing pressure on clinical structures. The development of new diagnostic tools, therefore, represents a significant challenge from a technological point of view, both in terms of overcoming current weaknesses in costs, accuracy, and performance, and from an analytical point of view in order to develop tools that are as operator-independent as possible. Recent breakthroughs in new technologies (such as cell phone-dependent technologies, paper-based procedures, and lab-on-a-chip devices) are paving the way for the next generation of point-of-care testing (POCT). Innovative assay devices, as well as efficient reagent storage techniques, are required for new POCT technologies. Nanomaterials of different forms, sizes, and compositions, such as carbon nanomaterials, quantum dots, gold and silver nanoparticles, mesoporous silica nanoparticles, and metal-organic frameworks (MOFs), have been created and characterized in recent years. Due to their specific physicochemical properties, MOF nanoparticles are increasingly being used in POCT to improve analytical performance and simplify testing techniques. MOFs have been used for colorimetric or electrochemical POCT and are used as carriers for plasmonic biosensors to be resistant to environmental conditions. This review will discuss the detailed role of MOF in POCT from 2016 to 2023, in addition to the chemical synthesis and characterization methods related to the uses and applications of MOF.

## 1. Introduction

Nowadays, conventional diagnostic procedures are frequently related to quantitative analysis of multiple biomarkers and biochemical properties in specimens within a central lab, with findings available only after many hours, if not days, of waiting. The effective miniaturization of diagnostic equipment for numerous biomarkers has resulted in the commercialization of sensitive and reliable point-of-care testing (POCT) technologies for disease diagnosis and monitoring in hospital emergency rooms and areas with limited resources [1–4]. The advantages of POCT technology over central laboratory testing include low-volume samples, minimal reagent consumption, miniature form factors, and quick turn-around times. A biological examination using POCT must be sensitive and specific, with quantitative results equivalent to existing laboratory-based procedures [5]. Medical diagnosis technology is undergoing a transformation due to the incorporation of computer technology, signal processing, biotechnology, micro- and nanotechnology, and microelectronics as its operating base progressively moves from centralized medical centers to private homes, motivated by the increasing demand for continuous real-time monitoring [6].

In recent years, the area of porous materials has witnessed substantial expansion, with the advent and fast development of metal-organic frameworks (MOFs) [7,8]. MOFs, or porous coordination polymers, are a form of complex porous material made up of inorganic clusters and organic ligands [9]. They are distinguished by great interior surface areas, with highly organized porosity, and a wide range of chemical and physical characteristics [10–12]. As a result, MOFs have demonstrated considerable potential in various applications such as ionic/molecular

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adsorption [13,14], gas separation [15], energy storage [16], catalysis [17,18], chemical and biosensing [19]. Chemical sensing is a procedure that employs analytical equipment with sensitive components that experience chemical changes when in contact with chemical substances, as well as a transducer that converts the chemical changes into detectable physical signals. One of the most potential applications of MOFs is chemical sensing, owing to their enormous libraries of metal centers and easily functionalized organic cages, which make them sensitive to many chemical and biological stimuli [20–22]. Fig. 1 depicts the growing number of publications on MOFs in different fields in the last two decades.

Owing to the urgent need for POCT, extensive efforts have been made to create transducers and readout devices of different sorts to improve the sensitivity, accuracy, and application of biosensors for POC diagnosis [23]. It is worth mentioning that the capacity to identify the "target" biomarker in a complex biological sample is regarded as the most crucial step in any diagnostic experiment. Antibodies are one of the most popular biorecognition components used in biodiagnostic equipment [24]. A common example is pregnancy testing using lateral flow tests based on immobilized antibodies [25,26]. Unfortunately, antibodies, like other proteins, are "fragile" in the sense that they degrade and lose bifunctionality when exposed to extreme circumstances such as elevated temperatures, elevated humidity, organic solvents, and proteolytic agents [27–30]. In resource-limited settings, certain challenges can arise when transporting, handling, and storing biosensors. These challenges may include inadequate facilities like refrigeration or electricity, limited awareness of proper handling precautions, and a lack of suitable packaging or sealing methods. As a result, the reliability of the bioanalytical results can be significantly compromised, which in turn restricts the practical applications of POC biosensors.

Therefore, MOF-based POC devices possess high potential due to their unique characteristics including great surface area, variable porosity, organic functioning, extendable shelf life, great thermal stability, and the ability to incorporate biomolecules into these hybrid materials to generate MOF biocomposites [7,31–33]. Certainly, MOFs represent an attractive basis to develop new systems for diagnostics. Fig. 2 summarizes the milestones in the development of MOF applications in POCT.

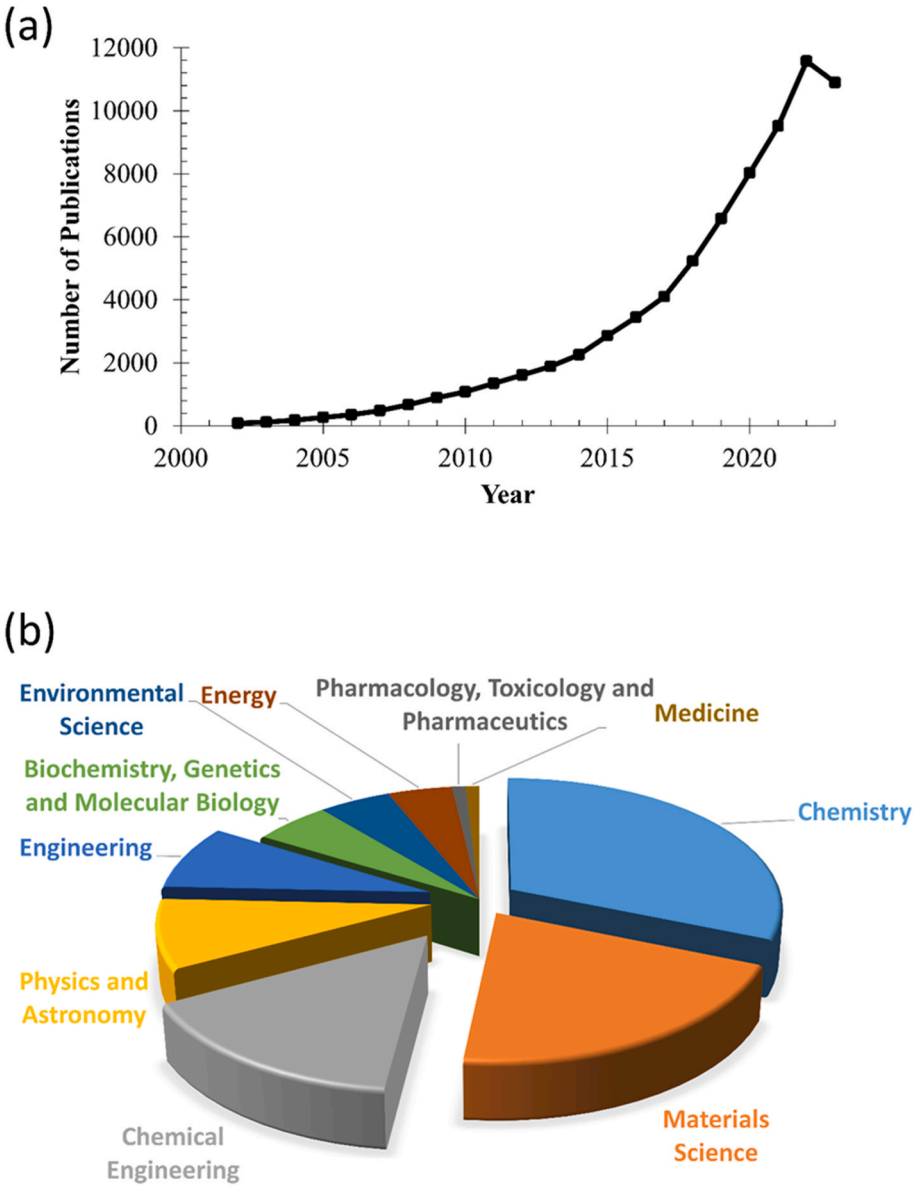


**Fig. 1.** (a) The increasing number of publications on MOF in the last 20 years according to the Scopus database, (b) The different fields of publications in MOF research.

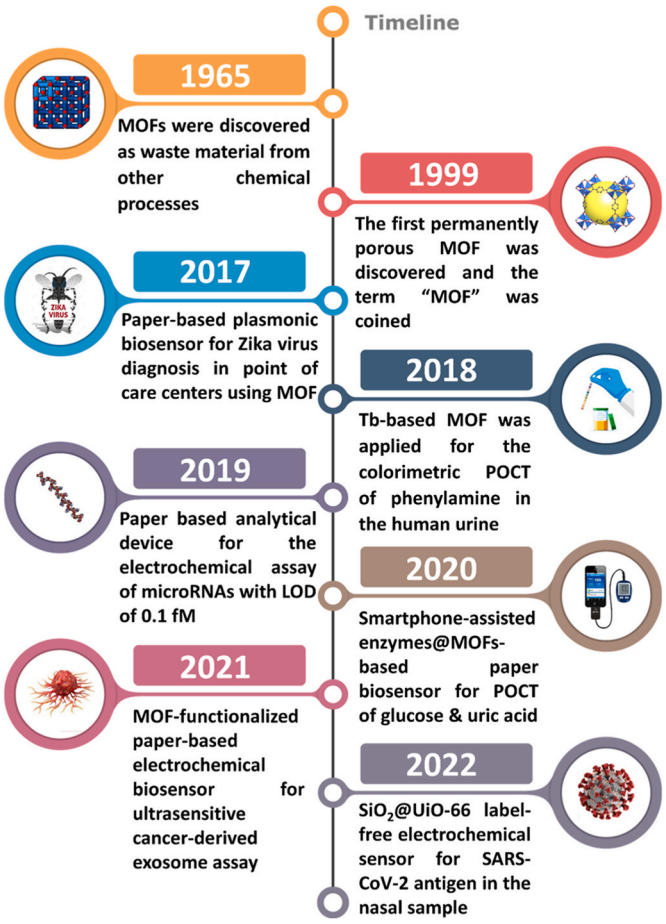


**Fig. 2.** Timeline of the development of MOFs in POCT.

In this work, the role of MOFs in POCT is being discussed for the first time. A deep understanding of the exact roles of MOFs in POCT is crucial due to the necessity of ongoing development in POCT to address the daily challenges posed by acute and chronic diseases. The purpose of this review is to emphasize the role of MOFs in colorimetric, electrochemical, and plasmonic biosensors for POCT.

Another novel element of the present work consists in a critical evaluation of the green profile of the use of MOFs in POCT through the application of the principles of Green Sample Preparation (GSP). Although GSP is gaining ground in the analytical field in order to evaluate the environmental impact of new sample preparation procedures, is still little known and/or used. For this reason, this review has dedicated a section in which this element is discussed and how MOFs can promote better "adherence" to the principles of GSP.

## 2. Synthesis of MOF

MOF synthesis has attracted a lot of interest in recent years because it allows for the creation of a broad variety of attractive structures that could also be useful in a range of applications related to porous materials. This encompasses more typical fields like catalysis, separation, and storage, which are dependent on host-guest interactions, pore size, and pore shape. Furthermore, biological applications or usages as sensor materials are actively being researched. There are different methods for synthesis of MOF as reported in Fig. 3 including conventional, microwave-assisted, sonochemical, electrochemical, and mechanochemical synthesis.

The conventional synthesis refers to the reactions that are carried out using electric heating with no process of parallelization. The reaction temperature is an important parameter in the process of synthesis, and two approaches are often defined, solvothermal and non-solvothermal, which govern the type of reaction setups that must be utilized.

Solvothermal reactions refer to reactions occurring in closed containers at autogenous pressures above the boiling point of the solvent [34]. As a result, non-solvothermal reactions occur below or near the boiling point at ambient pressure, simplifying synthetic needs. The latter reactions are further categorized as occurring at room temperature or at higher temperatures. It is worth mentioning that chemical reactions demand some type of energy input, and reactions halt only at temperatures near to 0 K. MOF synthesis is typically performed in a solvent at temperatures ranging from room temperature to around 250 °C. The energy is often delivered using traditional electric heating, in which heat is transmitted from a hot source, such as the oven, via convection. Energy can also be introduced by other sources, such as an electric potential, electromagnetic radiation, mechanical waves (ultrasound), or mechanically. The time, pressure, and energy per molecule supplied into the system are all directly tied to the energy source, and each of these factors can have a significant impact on the product created and its shape [35]. The conventional methods of MOF synthesis are well established, widely used, and can produce high-quality MOFs with good crystallinity. However, these methods require high temperatures and long reaction times, which makes these processes energy-intensive.

The interaction of electromagnetic waves with mobile electric charges explains microwave-assisted synthesis. Microwave ovens designed for materials synthesis provide monitoring of temperature and pressure during the reaction, allowing a more accurate control of reaction conditions. Microwave-assisted MOF synthesis has mostly been used to accelerate crystallization, produce nanoscale products, and increase product purity [36]. This is owing to the direct heating of the solvents and the observably increased nucleation rate. Microwave-assisted synthesis offers shorter reaction times compared to conventional methods with enhanced control over MOF properties. However, microwave-assisted synthesis has a limited capacity for large-scale synthesis and may require specialized microwave reactors.

Müller and coworkers [37] reported that electrochemical synthesis is able to exclude anions such as nitrate, perchlorate, or chloride throughout the synthesis, which is problematic for large-scale manufacturing processes. In addition to that, other advantages of the electrochemical approach for industrial processes include the ability to operate continuous operation and acquire a greater solids content than with traditional batch reactions. However, the electrochemical synthesis of MOFs is limited to specific MOF precursors that are electroactive, with potential challenges in achieving high yields and purity.

In the case of mechanochemical synthesis, mechanical force may cause a variety of physical events (mechano-physics) as well as chemical reactions [38]. The mechanical breakdown of intramolecular bonds is followed by a chemical transition in mechanochemical synthesis [38–41]. There are several reasons for the interest in mechanically activated MOF synthesis. A critical factor is linked to environmental impact. The reactions can be carried out at room temperature under solvent-free conditions. This synthetic route is certainly the best one to follow whenever the use of organic solvents can be avoided. Furthermore, the possibility of having short reaction times (between 10 and 60 min) often allows for quantitative reaction yields and products containing tiny particles. Furthermore, in some cases, metal salts can be replaced as the starting material by metal oxides, resulting in the creation of water as the only by-product. However, mechanochemical synthesis requires specialized milling equipment, with the potential for contamination due to milling media and equipment wear.

Sonochemistry is concerned with the chemistry that occurs when high-energy ultrasound is applied to a reaction mixture. The fundamental objective of sonochemical synthesis in MOF research was to develop a simple, rapid, energy-efficient, and ecologically acceptable room temperature approach [35]. Yet, sonochemical synthesis in MOFs has limited scale-up potential. Consequently, researchers select the synthesis method based on their specific requirements, such as

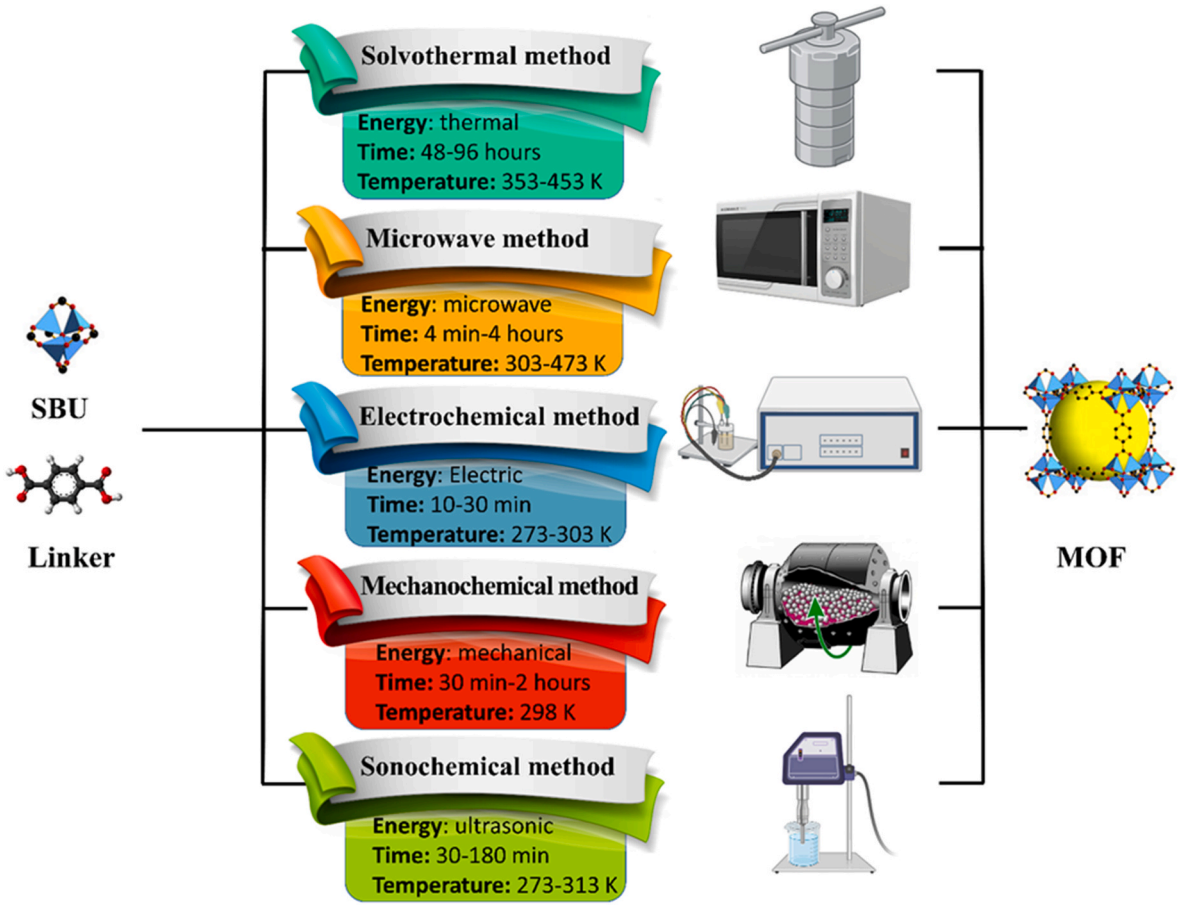


**Fig. 3.** Overview of MOF synthesis for POCT applications.

scalability, reaction time, available equipment, and desired MOF properties. Fig. 3 illustrates the methods of preparation of MOFs used in POCT applications.

## 3. Characterization and stability of MOF

After MOFs synthesis, their characterization should be done. The morphology of MOFs could be determined by one of the following techniques: scanning electron microscopy (SEM), atomic force microscopy (AFM), transmission electron microscopy (TEM), fluorescence microscopy, and Brunauer–Emmett–Teller (BET) [42]. While X-ray powder diffraction (XRPD), TEM, dynamic light scattering (DLS), and BET are used for crystal and size determination [42]. Chemical and elemental analysis could be determined by Fourier transform infrared spectroscopy (FT-IR), nuclear magnetic resonance (NMR), thermogravimetric analysis (TGA), mass spectroscopy, and atomic absorption spectroscopy (AAS). UV/Vis spectroscopy, photoluminescence spectroscopy, and Raman spectroscopy were used for the evaluation of the optical characters [42]. Electromagnetic characteristics could be determined by magnetic force microscopy (MFM), electron paramagnetic resonance (EPR), and vibrating sample magnetometer (VSM) [42]. SEM and field emission scanning electron microscopy (FESEM) are commonly used to investigate the morphology of the surface of MOF nanoparticles. Furthermore, utilizing TEM, the fine features of the interior structure of the MOFs could be observed [43]. TEM is a very versatile technology that can answer many concerns arising from the intricacy of the nano crystalline configuration of MOFs that standard imaging methods may not be able to determine.

The hydrodynamic size (to be considered as the diameter of a sphere that has the same translational diffusion speed as the particle) and the surface charge are determined by DLS and zeta potential analysis, respectively. The BET nitrogen adsorption/desorption technique is instead employed to evaluate the pore size distribution and surface area of nano MOFs [44].

X-rays are exploited in the case of XRD (X-ray diffraction) analysis, which provides information on the identification of the structure and phase of crystalline materials based on the diffraction pattern. In the case of crystalline compounds, it is sharp and narrow, while the diffraction pattern for amorphous compounds includes both a noise-related signal and generally broad peaks produced by non-crystalline compounds [45,46].

NMR spectroscopy is applied to monitor and confirm the existence of guest molecules inside the pores of MOFs and organic linkers. This technique is often applied also in the configuration for solid-state analysis as some MOFs are not soluble in any organic solvent and appear in the solid state [47,48].

FTIR is commonly used to confirm the appropriateness of a synthesis. In general, the FTIR signals used to detect functional groups in the structure of MOFs are mainly related to carbonyl groups (1800–1500 $cm^{-1}$), primary and secondary amino groups (3600–3300 $cm^{-1}$), and metal-oxygen bonding (600–400 $cm^{-1}$) [49]. X-ray photoelectron spectroscopy (XPS), compared to the previous ones, represents a quantitative spectroscopic approach that uses the photoelectric effect to examine the chemical state of the surface of the compound, its experimental formula, and the electronic state of the metal ions included in the structure of the MOF. This technique, therefore, represents a valid tool for characterizing the suitable ionic state of metal ions with a variety of electronic states used in the production of various MOFs [50,51]. Some MOFs show luminescence and fluorescent features as a result of delocalized π-electron and metal-to-ligand or ligand-to-metal charge

transfer, and they are employed in a variety of biological applications such as cell investigation and sensing [52]. Furthermore, when fluorescent materials such as gold nanoparticles and quantum dots are introduced into MOFs during the production process, photoluminescence spectroscopy as a way of interrogating the electrical structure of the MOFs is beneficial [53]. UV/Vis spectroscopy might be used to study organic linkers, medicinal compounds, and biological macromolecules containing π-electrons with high conjugation [54].

During the sample preparation process, contact surface with the sample should be maximized to increase yield and enhance selectivity, mechanical, thermal, and chemical stability. In the case of MOFs, the coordination and strength of the metal ion bond, the conformation, and size of the pores are the main elements influencing the final characteristics of the MOF and, consequently, its applicability [55]. The primary challenges in enhancing the chemical stability of MOFs are typically addressed with liquid water and water vapor. Therefore, it is advisable to focus on solutions in this regard. When considering structures like MOFs, it is important to note they have weak points at the nodes, especially related to the metal-linker bonds. In these areas of the structure, the formation of a protonated linker and a knot linked with hydroxide (or water) can be observed due to hydrolysis. These reactions are typically accelerated by acidic solutions, leading to the formation of the protonated linker. On the other hand, basic solutions tend to induce the formation of hydroxide. Given these challenges, the stability of MOFs should be evaluated in such solutions (as well as in a neutral environment) by examining signals from powder X-ray diffraction (PXRD) analysis [55]. When assessing the stability of MOFs, it is also crucial to consider that thermal deterioration can occur (resulting in breakage of the node-linker bond) and thus observe how thermal stability is directly correlated to the strength of this bond. Thermal degradation processes include phenomena like amorphization, fusion, dehydration, dehydrogenation, or graphitization [54–58]. To characterize MOFs thermally, TGA and differential scanning calorimetry (DSC) methods are commonly employed. TGA is highly useful for initial screening, while DSC is preferred for more detailed measurements related to the thermal properties (heat flow, phase transitions, and specific heat capacity).

From TGA experiments, it can be observed that between 50 °C and 100 °C, solvent molecules within the typical porosities of MOFs are released, while between 100 °C and 200 °C, the coordinated solvent molecules are released. At this stage, the TGA analysis shows a plateau (indicating whether the MOF has a porous crystalline structure), ending at the temperature where partial disintegration of the MOF structure and partial volatilization begin [55].

Certain critical issues related to the thermal stability of some MOFs are the main limitations of their applications in areas such as carbon dioxide capture from exhaust gases and their use as catalysts in methanol production from synthesis gases ($H_2$ and CO). In recent years, hydrothermally stable MOFs have been synthesized and utilized as heat accumulators (they absorb and desorb aqueous vapors) [58]. In such cases, their stability is evaluated by exposing them to steam at various temperatures and pressures and then measuring parameters such as surface area or porosity using the PXRD technique [59,60].

MOFs are known for their high porosity, which inherently reduces their mechanical stability. Consequently, MOFs are less mechanically stable compared to zeolites, as anticipated. Under mechanical loading, this instability may manifest as phase transitions, partial collapse of pores, or even amorphization [61–64].

## 4. Applications of MOF in POCT

The rising danger of epidemic or chronic illnesses, as well as the high cost of operative pharmaceuticals, has resulted in greater support, discussion, and desire for the use of POC diagnostic skills [65]. Now, biosensors made of various materials and constructed using various detection techniques are being researched to overcome the present barriers to efficiently detecting these diseases. MOFs have been identified as a viable material for enhancing the detection limit and specificity of biosensors for the detection of these diseases [32,66–68]. In the following section, the role of MOFs in POCT will be discussed in detail.

### 4.1. Applications of MOF in colorimetric POCT

Usually, colorimetric-based POCT employs colorimetric test strips for detection and quantification, which depend on the values of chromaticity in images captured by the mobile camera to assess the level of concentration [69–71]. In addition to test strip fabrication, microfluidic paper-based analytical devices (μPADs) [72] play an important role in POCT [73]. The principle of the color change of the MOF in colorimetry POCT could depend on using direct colorimetric change based on a certain reaction. Luan and coworkers [73] used cerium-based MOF for the colorimetric assay of uric acid and glucose, as indicated in Fig. 4. In this work, the authors built the Ce-MOF-based OPSlipChip for selective uric acid and glucose detection to provide a point-of-care testing platform. To replace the lateral flow test, this tool used an externally actuated method and a molecular threading strategy, inspired by the previously disclosed Slip Chip technology and molecular threading-dependent mass transport strategy. The functional parts of the two sheets were not aligned while the chip was in the "OFF-state," and the hydrophobic part coated with paraffin wax was under the reaction regions of the top sheet. As a result, the sample may be retained in the reaction areas through incubation, and then the conversion from the target analyte to $H_2O_2$ can be completed. The loaded OPSlipChip was transformed into the "ON-state" for colorimetric analysis after incubation by sliding. Due to the slide caused by external actuation, the liquid sample was able to move to the desirable locations. The molecular threading was triggered during the "ON-state". The sheet, when coupled with Ce-MOF, will cause rapid capillary pumping of water molecules and molecular threading of solute via solute-solvent interaction in the direction of gravity. Compared to linear mass transfer in lateral flow, the transit distance of molecular threading in this system was substantially shorter.

An alternative strategy in the use of MOF in colorimetric POCT consists of preparing a fluorescent strip with the help of luminescent MOFs, the color of which is modified with the addition of the target analyte with the help of the UV lamp. This strategy was successfully applied for POCT related to several diseases including Parkinson's disease [74,75], cancer [76,77], COVID-19 [78], Alzheimer's disease [79], diabetes [80,81], liver dysfunction and bone disorders [82]. However, this approach is not very attractive in POCT due to the need for a UV lamp, which is generally not available in most clinics. This makes the application of these MOF-based fluorescent strips not that practical.

Noble metal nanomaterials, especially nanoclusters composed by Au and Ag, have attracted increased attention in recent years as preferred options for fluorescent probes, owing to several exceptional advantages such as high fluorescence (FL) intensities for fluorometric detections [83–87]. An enormous challenge in terms of conservation (i.e., optical blenching) may be used for fluorescent nanoprobes (i.e. photosensitive Ag nanoparticles), particularly those coated on test strips, which may prevent fluorometric test strips from being used in large-scale analysis applications. Cai and coworkers [76] developed a luminescent test strip for POCT using gold-silver (Au–Ag) nanospheres and ZIF-8, for investigating trace cysteine (Cys) in Hela cells. Au–Ag bimetallic nanoclusters were first synthesized using protein-based biomineralization and then harvested via a desolvation process to create Au–Ag nanospheres with high fluorescence selectively suppressed by Cys. Nanospheres were coated onto test strips before being coated with ZIF-8 via a vacuum-assisted rapid drying technique with superhydrophobic patterns. It was revealed that the test strips could not only create uniform coatings of fluorescent nanoprobes, but also increased fluorescence, environmental and storage stability due to the ZIF-8 shell, as shown in Fig. 5.

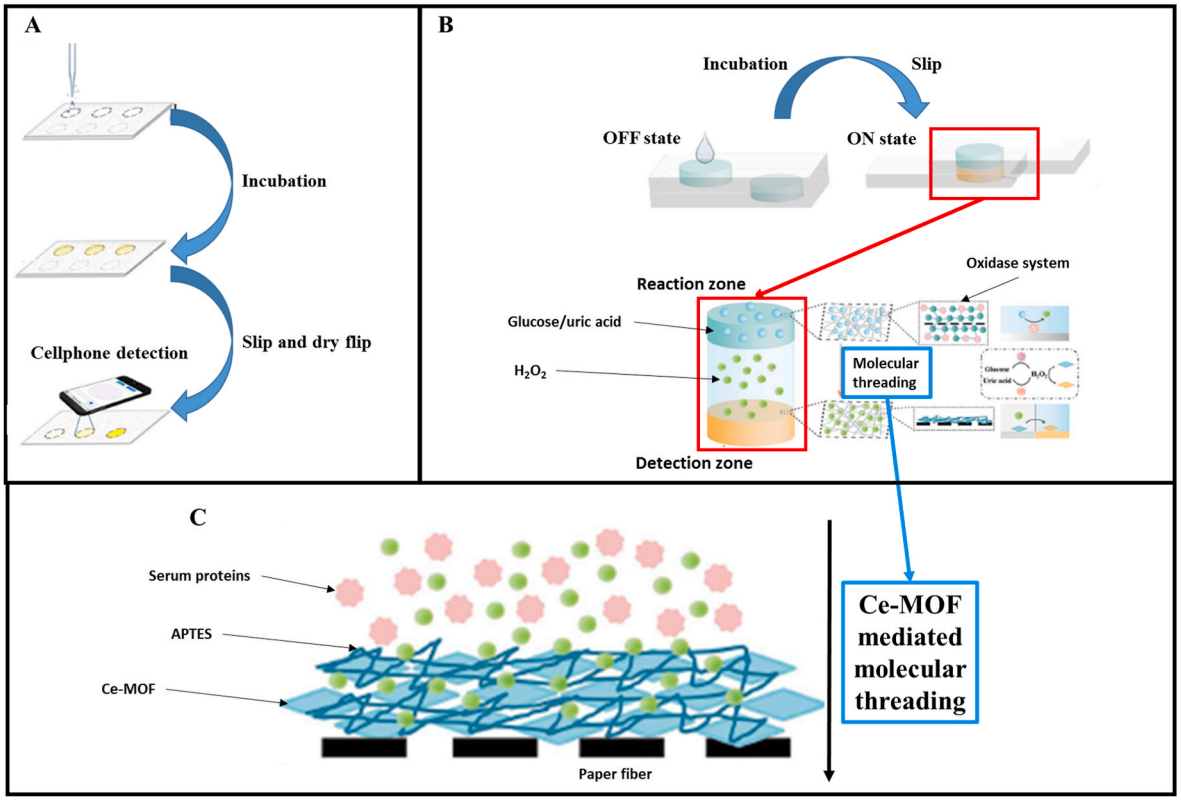


**Fig. 4.** (A) Schematic representation of the procedures on an OPSlipChip based on CEF-MOF; (B) The Ce-MOF-based OPSlipChip's operational concept and functional change; (C) Ce-MOF mediated molecular threading strategy creates a bio-like barrier for proteins in serum.

In addition to assessing Cys in biological samples, the fluorometric test strips aided in the determination of Cys in Hela cells with a linear range of concentrations from 0.0032 to 32.0 μM, making them promising for POCT of low-level Cys for early clinical diagnosis of diseases such as cancer. Furthermore, the proposed technique for producing stable and uniform test strips using MOF coatings and superhydrophobic templates could be adapted for creating diverse solid-state test platforms for a wide range of analytical applications.

Yu and coworkers [82] developed lanthanide MOF based paper microchip for visual dopamine assay. The authors suggested a ratiometric fluorescence dopamine assay that combines a particular dopamine-resorcinol chemical reaction with a multifunctional lanthanide metal-organic framework (Ln-MOF). First, Eu-BTC (1,3,5-benzenetricarboxylic acid) was synthesized and then modified to produce Cu@Eu-BTC, which performs many functions at the same time, including internal fluorescence standard, nanoreactor, cooperative catalytic effects and enhancement of color change. The Cu@Eu-BTC dispersion-based approach was ultrasensitive (limit of detection, LOD, was 0.01 μM) and had a broad-spectrum linear response (0.04–30 μM) to dopamine in the blood. Even more critically, it showed high selectivity for dopamine even in the presence of adrenaline and norepinephrine analogues. As shown in Fig. 6, a portable and visible dopamine test was designed using a simple, functional paper microchip. The paper microchip was created by coating glass fiber filter paper with Cu@Eu-BTC and resorcinol. Point-of-care dopamine testing can be accomplished with the help of the visual testing machine and the MOF paper microchip. Table 1 summarize the colorimetric applications of MOF in POCT.

### 4.2. Applications of MOF in electrochemical POCT

As reported in the previous sections, accessible POCTs become increasingly important to promote individual health self-assessment and reduce drastically the infection in chronic patients, whose mortality from infection is worrying. For example, POCTs for heart rate, blood pressure, and glucose can proficiently monitor key chronic diseases and reduce serious or unintended harm through rapid diagnosis [33].

Electrochemical signal sampling plays a key role in POCT. In this field, the use of miniaturized electrochemical sensors (MEC) to detect traces of analyte, such as small organic molecules, metal ions, and biomolecules should be highlighted [92–95]. Such measurements are made by considering changes in current, voltage, potential or impedance, which are mainly caused by the redox process of molecules [89]. The electrodes used in this type of measurement are modified in order to increase their selectivity by conjugation with specific recognition elements (aptamers, antibodies and receptors of interest), while maintaining simplicity, ease of use, reduced preparation of the sample, fast analysis times, portability and low cost [90]. Due to the superior benefits of electrochemical (EC) technologies, significant research efforts are currently being prepared to create new POCT sensors for trace quantities analysis in numerous fields directly related to environmental monitoring, food safety, and health care [91–93].

The improvement of electrical designs and interconnected circuits for readout systems allows for a low-cost biosensor production method. The combination of bioelectronics with the knowledge can result in the development of nanoscale equipment capable of competing with traditional systems [94,95]. As indicated previously, MOFs are a distinct family of materials that are porous, crystalline, and self-assembled by single or multi metal ions or metallic clusters, as well as organic linkers via coordination bonds [96–99]. Some research highlights the use of MOFs in integrated analytical equipment. However, due of their weak electron transport capability, MOFs alone are regarded electrically insulating, preventing their direct usage in electrochemical sensing [100–102]. To solve this shortcoming, MOF-composites platforms were developed, in which MOFs were combined with conducting materials to improve electron transmission and operate as electrochemical sensors [103,104]. Palanisamy and coworkers [9] developed MOF-nanohybrids

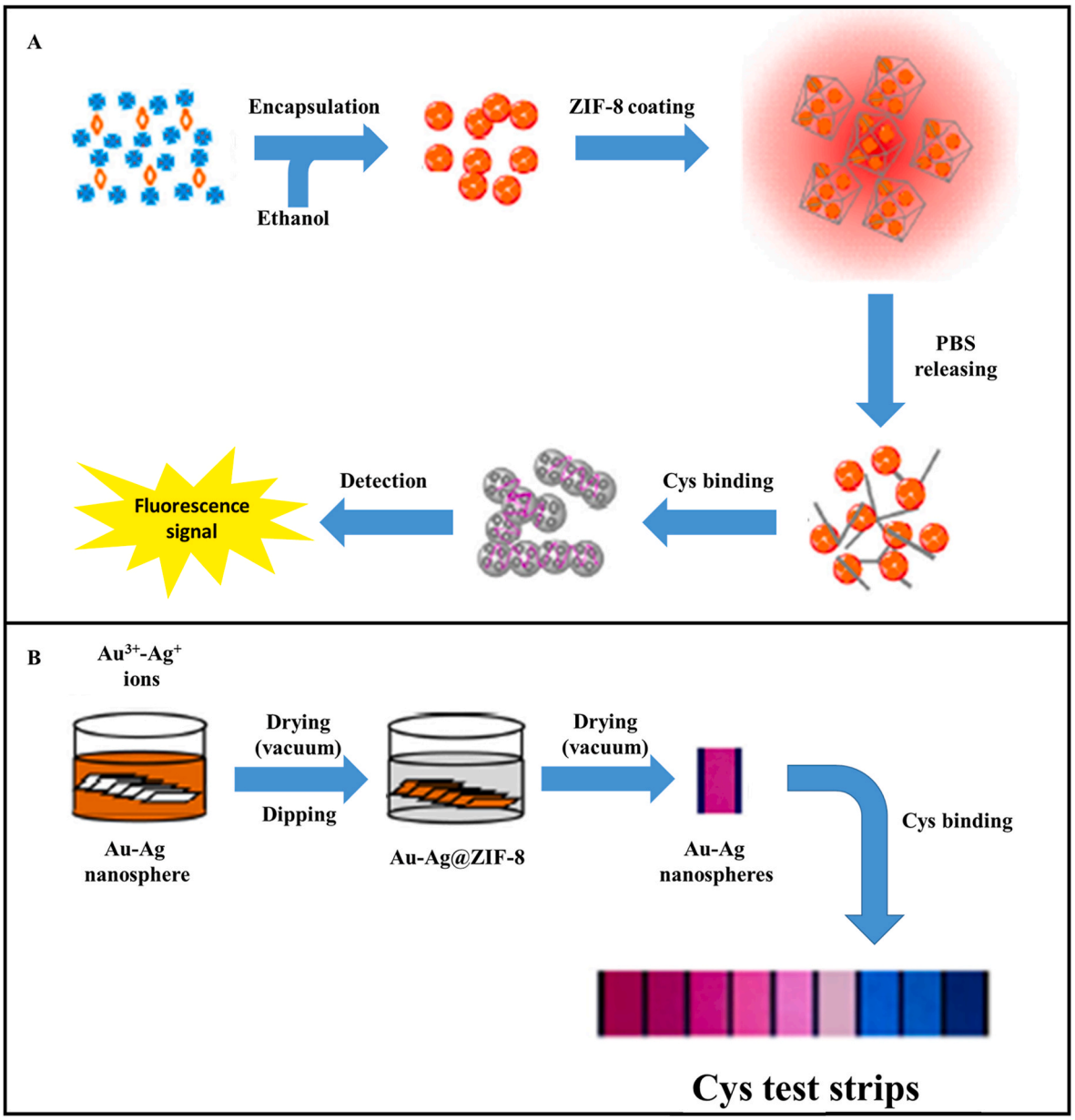


**Fig. 5.** (A) The primary procedure and mechanism of Au–Ag@ZIF-8 based fluorometric test strips for Cys analysis, including Au–Ag coating, ZIF-8 shelling and Cys immersion assays. (B) The reactions on which the device is based to detect Cys via BSA encapsulation of Au–Ag nanospheres, ZIF-8 shelling and release of Au–Ag@ZIF-8 triggered by PBS and the Cys-induced fluorescence quenching of Au -Ag@ZIF-8.

for integrated POCT of SARS-CoV-2 viral antigen/pseudo virus utilizing electrochemical biosensor chip. As reported in Fig. 7, the creation of a biosensor test strip for the detection of SARS-CoV-2 viral antigens utilizing a handheld portable POC equipment and comparing it to a regularly used electrochemical instrument was developed.

When the performances are evaluated in buffer and serum medium, the LOD was determined to be 6.68 fg/mL and 6.20 fg/mL, respectively, with good precision and specificity. In this configuration, the $CoFeBDCNH_2$-MOF and $CoFe_2O_4$ nanomaterials as MOF nanohybrids allowed synergistic effects to be achieved, further improving performances. From studies evaluating the electrochemical activity of the various materials, it was possible to investigate the conductive impact of each material in order to finally select the best material to use for the detection of the SARS-CoV-2 viral antigen. Accordingly, the sensing ability of the newly fabricated electrodes was investigated using electrochemical impedance spectroscopic (EIS) experiments. Finally, MOF nanohybrids generated after a 120-min reaction period were used as a substrate for SARS-CoV-2 viral antigen detection as they had the highest conductivity among all tested materials.

Wei and coworkers [33] developed Cobalt-MOF modified carbon cloth (CC)/paper hybrid electrochemical button-sensor for nonenzymatic glucose diagnostics. In this work, a compact, resilient, and easy-to-use electrochemical analytical chip was created for non-enzymatic quantitative glucose detection using a Cobalt-MOF (Co-MOF/CC/Paper). A highly integrated electrochemical analytical chip with a flexible Co-MOF/CC sensing interface has been successfully developed, substantially improving the specific area and catalytic sites compared to the standard flat electrode (Fig. 8).

The button-sensor enabled quick quantitative detection of glucose in a variety of complex biological matrices, including serum, urine, and saliva, with the necessary selectivity, stability, and durability. The developed nanozyme-based electrochemical analytical chip accomplished reliable non-enzymatic electrocatalysis with the benefits of low cost, high environmental tolerance, and simplicity of manufacture and

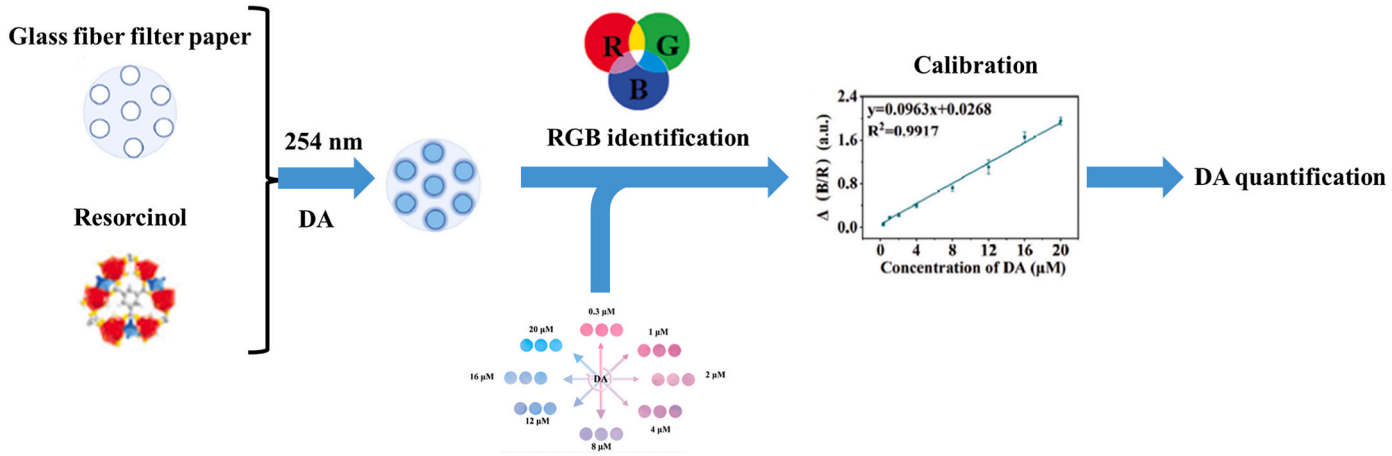


**Fig. 6.** The visual dopamine analysis procedure and quantification of dopamine in serum samples fortified with different concentration levels (0.3–20 M) using the MOF paper microchip and a smartphone-based visual analysis device. (B/R) represents the difference in the Δ(B/R) value between the experimental group (with a definite level of dopamine) and the control group (without the analyte).

showed significant promise for the use of quick on-site analysis in personalized diagnosis and disease prevention.

### 4.3. Applications of MOF in POCT plasmonic biosensor

Surface plasmonic resonances (SPRs), which consist of the resonant coupling of electromagnetic waves to the collective oscillations of free electrons in metals, are widely used due to the possibility of controlling the properties of light at the nanoscale [105,106]. The ability to amplify and confine light to dimensions significantly smaller than the incident wavelength has opened up new paths in integrated nanophotonic and miniaturized optoelectronic systems. Light is intensified and confined at the interface of two media with dielectric constants of opposite signs, often a dielectric and a metal, and decays rapidly as it is dragged away from contact. Due to their integration into microfluidic systems and great sensitivity to changes in dielectric characteristics at the interface, plasmonic platforms are suitable for low-cost POCT devices. (mainly caused by adsorption processes) [107,108].

Owing to their greater binding affinity and selectivity, antibody-antigen interactions serve as the basis for a variety of standard bioassays such as enzyme-linked immunosorbent assay [109], immunoblotting [110], and immune precipitation [111]. In this context, and thanks to the rapid development and widespread application of diagnostic procedures in the biomedical field, the development of biosensors in the lab-on-a-chip configuration has been observed, in which antibodies are widely used as an extremely selective towards the analytical target through multiple signal transduction platforms (electrochemical [112], magnetic [113], and optical [114]). The main problem related to the use of antibodies is their low stability at room temperature and high temperatures, as well as limitations regarding their stability in non-aqueous liquids (as occurs in the case of transducer surfaces after the immobilization process). To maintain their bio-functionality (recognition capability), antibody-based diagnostic reagents and biosensor chips must be kept at a closely controlled temperature (refrigerated). This important requirement involves the use of a supply chain of individual points of sale and use at a controlled temperature (the so-called “cold chain”), in which the temperature at which the handling and movement procedures are promptly verified and maintained. The cold chain, therefore, requires an increase in costs and a greater environmental impact compared to conventional procedures. Furthermore, it is not always feasible in pre-hospital settings and/or with limited resources such as those possibly present in urban and rural clinics, developing countries, disaster-stricken areas, and battlefields, where maintaining specific conditions may not always be feasible [115]. From this perspective, the development of innovative and alternative methods to preserve the biorecognition capacity of antibodies is of fundamental importance, thus reducing or eliminating the need for the cold chain while simultaneously increasing the shelf life, the reproducibility of the measurements, and the ease of use.

To provide a possible solution to this problem, the possibility of encapsulating a wide variety of biomolecules in MOFs by growing in the presence of the biomolecules in mild biocompatible circumstances (aqueous solution and through reactions at room temperature) is currently being studied [116]. This aspect also allows the activity of the encapsulated biomolecules (for example, enzymes) to be protected and maintained even in unfavorable environmental conditions (high temperatures and organic solvents) [117]. Wang and coworkers [118] developed MOF coatings to be applied in particular to maintain the biological recognition of antibodies immobilized on sensor surfaces subjected to high temperatures. Unlike other methods, which involved mixing protein (enzyme) with MOF precursors in solution, ZIF-8 was produced on bio-nanoconjugates immobilized on gold nanorods. A simple water rinse process just before utilizing the biochip totally dissolved the MOF protective layer, restoring the sensor surface’s bio-functionality (Fig. 9).

Due to its high sensitivity, cost efficiency and great potential for use in diagnostics, a plasmonic nanobiosensor based on localized surface plasmon resonance refractive index sensitivity has been used as a platform to monitor various phases of fabrication, including conjugation of antibodies onto the surface of plasmonic nanostructures, MOF formation and removal [119]. It is worth mentioning that the detection of bioanalytes was also possible. The results demonstrated using IgG/anti-IgG as a test system, indicating that the MOF layer significantly enhanced the stability of the model antibody at room temperature, 40, and 60 °C.

Wang and coworkers [120] developed biochips with MOF coating for POCT. In this work, a localized surface plasmon resonance (LSPR) refractive index sensitivity-dependent plasmonic nanobiosensor was employed as a POC biosensor model, with gold nanorods (AuNRs) as nano transducers. The manufacturing steps of the plasmonic biosensor (including antibody attachment to the surface of AuNRs, growth and removal of the MOF layer, and bioanalyte detection) were evaluated by monitoring the LSPR wavelength shift of AuNRs. In addition to this, the ability of the MOF-based approach to resist several adverse environmental conditions (including increased temperature, organic solvent and proteolytic degradation) which would result in the denaturation of antibodies and loss of bifunctionality of the biochips was evaluated, as indicated in Fig. 10.

The findings indicated that the ZIF-8 protective layer significantly increased the stability and usability of biochips for use in resource-limited situations, as well as in poor and middle-income nations. After

**Table 1**
Colorimetric applications of MOF in POCT.

| Sample | Sample volume | Analyte | MOF component | MOF synthesis | Colorimetric principle | Visual sensing tool | Linearity range | LOD | %RSD | REF |
|---|---|---|---|---|---|---|---|---|---|---|
| Serum Urine | N/A | Glucose | $EU^{+3-}$Zr- 2,2′-bipyridine-5,5′-dicarboxylic acid | Conventional synthesis (solvothermal) | FLD based colorimetric assay | POC Diagnostics logic detector | 0.1 μM–10 μM, 10 μM–10 mM,>10 mM) | 0.23 μM and 0.25 μM in urine and serum | N/A | [69] |
| Serum | 150 μL | Uric acid and glucose | Cerium terephthalic acid | Conventional synthesis (non-solvothermal) | Direct colorimetric assay | The origami paper Slip Chip (OPSlipChip) | (0–25 mM) for glucose and (0–1000 μM)for uric acid | 0.069 mM and 39.6 μM for glucose and uric acid respectively. | N/A | [74] |
| Serum | N/A | Dopamine | Terbium ZrCl4 and H4btec | Conventional synthesis (solvothermal) | FLD based colorimetric assay | Portable test paper | 0–350 μM | 0.06 μM | 2.05 and 5.86. | [75] |
| Serum sample | 30 μL | Dopamine | Eu–BTC (1,3,5-benzenetricarboxylic acid) | Conventional synthesis (non-solvothermal) | FLD based colorimetric assay | Paper microchip | 0.3–20 μM | 0.08 μM | ≤6.83% | [76] |
| Serum samples | 100 μL | Glutathione and cysteine | Ag/Eu@Ni-MOF | Conventional method (hydrothermal) | FLD based colorimetric assay | N/A | 5–250 μM | 0.20 μM and 0.17 μM for cysteine and glutathione respectively | N/A | [80] |
| Human blood | 2 μL | Glucose and peroxide | Cobalt -terephthalic acid | Conventional synthesis (solvothermal) | FLD based colorimetric assay | Paper-based devices | 50 μM - 15 mM | 16.3 and 3.2 μM | 3.47 | [81] |
| Human serum | N/A | Alkaline phosphatase activity | Cu@Eu-BTC | Conventional synthesis (solvothermal) | FLD based colorimetric assay | Portable assay tube | 1–12 U/L | 0.24 U/L | ≤9.5 | [82] |
| Human urine | N/A | phenylamine | Terbium −2,2-bipyridine-5,5-dicarboxylic acid | Conventional synthesis (solvothermal) | FLD based colorimetric assay | Paper strip | 0.005–5 mg/mL | 5 μg/mL | 3–7% | [88] |
| Gastric juice | 5 μL | Acidity sensor | 1-hydroxypyrene@ Co/Tb-dipicolinic acid | Conventional synthesis | FLD based colorimetric assay | Paper-based pH microsensor | 0.3–7.8 | N/A | <5.4 | [89] |
| Solid pharmaceuticals | N/A | Water | Eu-dipicolinic acid/2-aminophthalic acid | Conventional (non-solvothermal) | FLD based colorimetric assay | Paper-Based Water Microsensor | 0−100% v/v | 0.01% v/v | ≤5.8 | [90] |

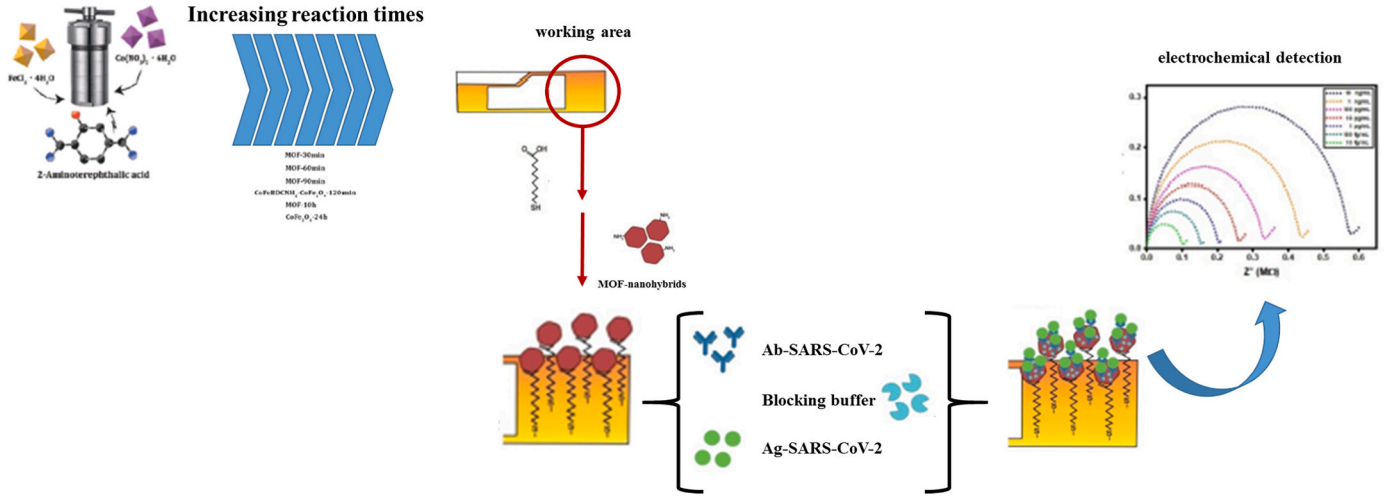


**Fig. 7.** Time-dependent one-step-one-pot hydrothermal synthesis scheme of CoFeBDCNH$_2$-CoFe$_2$O$_4$ MOF nanohybrids and other products with increasing reaction times to produce and detect SARS-CoV-2 viral antigen using portable device.

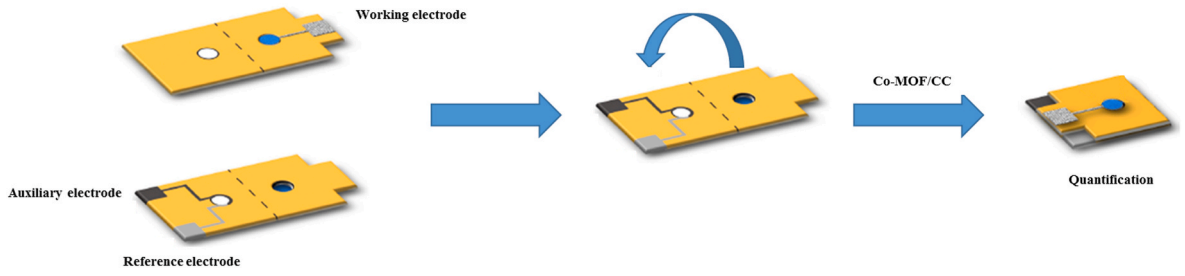


**Fig. 8.** Pictures of the button sensor and 3D diagram of the analysis procedure.

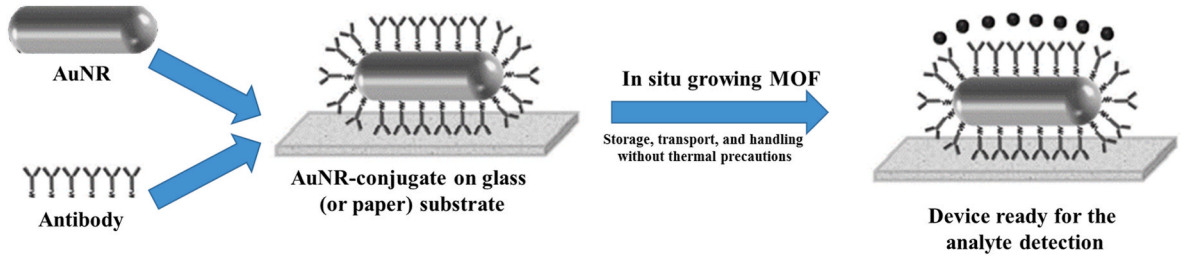


**Fig. 9.** Diagram relating to the process of using MOFs to increase the thermal stability of antibody-based plasmonic biochips, which would eliminate the cold chain and allow their use in environments with limited resources.

a day of incubation at temperatures up to 80 °C, the ZIF-8-coated biochips retained more than 80% of their identification capacity, serving as a proxy for long-term storage at room temperature. High-temperature storage efficacy can be increased by extending the growth time and thickness of the ZIF-8 film, underlining the need for complete encapsulation of the antibody.

## 5. Evaluation of the green profile

A very important element to take into consideration also concerns the impact of the procedure on the environment. If green chemistry (GC) was born in the 90s and green analytical chemistry (GAC) in the early 2000s, given the current state of knowledge it is essential to also consider green sample preparation (GSP) [121–123]. The GSP considers 10 fundamental principles linked to the critical step of sample preparation:

Principle 1. Favor *in situ* sample preparation
Principle 2. Use safer solvents and reagents
Principle 3. Target sustainable, reusable and renewable materials
Principle 4. Minimize waste
Principle 5. Minimize sample, chemical and material amounts
Principle 6. Maximize sample throughput
Principle 7 . Integrate steps and promote automation
Principle 8. Minimize energy consumption
Principle 9 . Select the most environmentally friendly post-sample preparation setup for analysis
Principle 10 . Ensure safe procedures for the operator.

In particular, considering these principles and applying them to metal organic frameworks in point of care testing, in all the various declinations and configurations covered in this review, it is immediately clear how they respond perfectly to several points. Specifically:

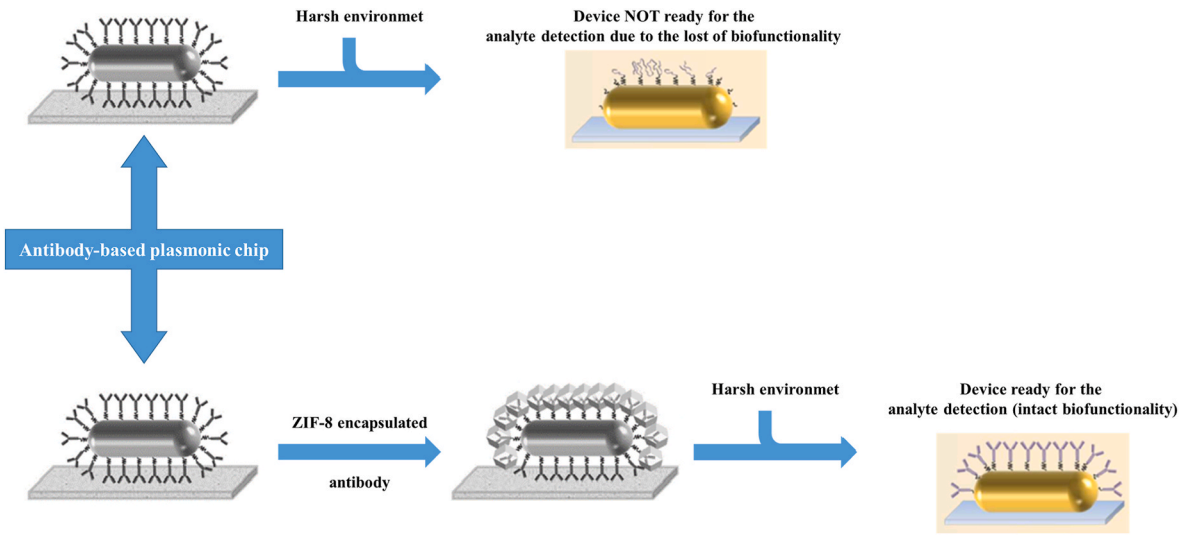


**Fig. 10.** Scheme of how a ZIF-8 encapsulated antibody manages to maintain its biofunctionality even when subjected to extreme environmental conditions, significantly increasing the reliability and usefulness of biochips in resource-limited settings.

- ✓ Principle 1. Favor *in situ* sample preparation - these are metal organic frameworks in point of care testing systems that do not require particular sample treatment procedures and therefore can be considered as "*in situ*" or, in some cases "*on line*" procedures;
- ✓ Principle 2. Use safer solvents and reagents - solvents are often not necessary, the biological sample is used directly to obtain the instrumental response for the analysis;
- ✓ Principle 4. Minimize waste and Principle 5. Minimize sample, chemical and material amounts - metal organic frameworks in point of care testing devices generally require a minimum amount of sample and/or solvents, as they are portable (or wearable) devices, resulting in reduced waste;
- ✓ Principle 7. Integrate steps and promote automation - the use of these metal organic frameworks in point of care testing devices allows the reduction of sample manipulation with consequent reduction of waste, reduction of possible errors in the measurement with consequent improvement in the precision and trueness of the procedure. In particular, this point is widely respected by wearable devices;
- ✓ Principle 8. Minimize energy consumption - compared to "classic" (HPLC-UV/Vis, GC-FID) or hyphenated (HPLC and GC-MS) configurations, a portable/wearable device based on metal organic frameworks powered by a small battery certainly shows a much better green profile;
- ✓ Principle 9. Choose the greenest possible post-sample preparation configuration for analysis - simple, readily available detection such as the use of smartphones, desktop scanners, paper strips are the basis for a green profile in general terms
- ✓ Principle 10. Ensure safe procedures for the operator - speaking of POCT and portable and/or wearable devices, it is clear how these ensure the safety of the operator/patient.

## 6. Perspectives and conclusion

MOFs are materials with extremely high surface areas and organized porous cages that have been studied over the past decades. Due to their design flexibility and tendency towards functionalization, they have shown promise in a variety of applications, including chemical sensing. As a result, they have been recognized as sophisticated materials with the potential for use in analytical instruments for chemical and biochemical sensing applications where high sensitivity is required, such as in environmental monitoring and personal diagnostics. It is worth indicating that MOFs have a high surface area for adsorption, a coherent pore structure to govern mass transport, and a wide variety of physical characteristics, including chemoresistant, electrical, and optical capabilities, which make them excellent for chemical detection. Each type of MOF in POCT offers unique advantages and disadvantages, which should be considered based on the specific requirements of the application. Colorimetric MOF-based sensors have high selectivity, producing relatively stable colors that can be detected by naked eye, but these sensors have limited dynamic range compared to the other detection methods. Electrochemical MOF-based sensors offer Improved sensitivity, and less vulnerability to interference, but the long term stability of electrodes should be taken into account besides the probable matrix effect [124]. Plasmonic MOF-based biosensor offer real-time monitoring capabilities, with a high potential for label-free detection, but the experimental design and optimization could be challenging, in addition to the overall high cost.

POCT could be performed using smartphones, μPADs, and simpler devices. Nowadays, the concern of POCTs tends towards wearable sensor. Traditional public health systems are plagued by limited, delayed and sometimes inefficient medical services, particularly in the face of the pandemic and an aging population. Wearable and portable sensors provide immediate access to health monitoring without the need for sophisticated systems. Wearable and portable sensors are becoming increasingly popular due to their ability to provide frequent and continuous monitoring of physiological data through dynamic, non-invasive assessments of biomarkers present in biological fluids such as tears, sweat, interstitial fluid, and saliva. Current improvements have focused on creating optical and electrochemical wearable sensors, as well as non-invasive monitoring of biomarkers such as metabolites, hormones, and microorganisms. Microfluidic sampling, multimodal sensing and portable systems have been combined with flexible materials to improve wearability and ease of operation. Although wearable sensors show promising results and increased reliability, a better understanding of the relationship between target sample concentrations in blood and non-invasive biological fluids is needed.

By combining traditional textiles with diagnostic, therapeutic and protective medical devices, e-textiles can be used on the human body as POC platform technologies, keeping an eye on the patient's vital signs and putting treatment plans in place around to the clock. Therefore, our prospects of integrating MOFs into wearable sensors and electronic fabrics will increase significantly in the coming years.

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## Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## References

[1] Y. Hou, C.-C. Lv, Y.-L. Guo, X.-H. Ma, W. Liu, Y. Jin, et al., Recent advances and applications in paper-based devices for point-of-care testing, J. Anal. Test. 6 (2022) 247–273, https://doi.org/10.1007/s41664-021-00204-w.

[2] Z. Zhang, P. Ma, R. Ahmed, J. Wang, D. Akin, F. Soto, et al., Advanced point-of-care testing technologies for human acute respiratory virus detection, Adv. Mater. 34 (2022) 1–39, https://doi.org/10.1002/adma.202103646.

[3] A. Singhal, A. Parihar, N. Kumar, R. Khan, High throughput molecularly imprinted polymers based electrochemical nanosensors for point-of-care diagnostics of COVID-19, Mater. Lett. 306 (2022) 130898, https://doi.org/10.1016/j.matlet.2021.130898.

[4] Y. Hang, J. Boryczka, N. Wu, Visible-light and near-infrared fluorescence and surface-enhanced Raman scattering point-of-care sensing and bio-imaging: a review, Chem. Soc. Rev. 51 (2022) 329–375, https://doi.org/10.1039/C9CS00621D.

[5] Q. Song, X. Sun, Z. Dai, Y. Gao, X. Gong, B. Zhou, et al., Point-of-care testing detection methods for COVID-19, Lab Chip 21 (2021) 1634–1660, https://doi.org/10.1039/D0LC01156H.

[6] C. Wang, M. Liu, Z. Wang, S. Li, Y. Deng, N. He, Point-of-care diagnostics for infectious diseases: from methods to devices, Nano Today 37 (2021) 101092, https://doi.org/10.1016/j.nantod.2021.101092.

[7] R.M. Abdelhameed, S.F. Hammad, I.A. Abdallah, A. Bedair, M. Locatelli, F. R. Mansour, A hybrid microcrystalline cellulose/metal-organic framework for dispersive solid phase microextraction of selected pharmaceuticals: a proof-of-concept, J. Pharm. Biomed. Anal. 235 (2023) 115609, https://doi.org/10.1016/j.jpba.2023.115609.

[8] H. Xiong, P. Li, F. Cun, H. Chen, J. Kong, Methylene-blue-encapsulated metal-organic-framework-based electrochemical POCT platform for multiple detection of heavy metal ions in milk, Biosensors 13 (2023) 783, https://doi.org/10.3390/bios13080783.

[9] S. Palanisamy, L.Y. Lee, C.F. Kao, W.L. Chen, H.C. Wang, S.T. Shen, et al., One-step-one-pot hydrothermally derived metal-organic-framework-nanohybrids for integrated point-of-care diagnostics of SARS-CoV-2 viral antigen/pseudovirus utilizing electrochemical biosensor chip, Sensor. Actuator. B Chem. 390 (2023) 133960, https://doi.org/10.1016/j.snb.2023.133960.

[10] Z. Sun, Y. Liao, S. Zhao, X. Zhang, Q. Liu, X. Shi, Research progress in metal–organic frameworks (MOFs) in CO 2 capture from post-combustion coal-fired flue gas: characteristics, preparation, modification and applications, J. Mater. Chem. A 10 (2022) 5174–5211, https://doi.org/10.1039/D1TA07856A.

[11] A.L. Sutton, L. Melag, M.M. Sadiq, M.R. Hill, Capture, storage, and release of oxygen by metal–organic frameworks (MOFs), Angew. Chem. Int. Ed. 61 (2022) e202208305, https://doi.org/10.1002/anie.202208305.

[12] Z.-J. Wang, Q. Li, L.-L. Tan, C.-G. Liu, L. Shang, Metal–organic frameworks-mediated assembly of gold nanoclusters for sensing applications, J. Anal. Test. 6 (2022) 163–177, https://doi.org/10.1007/s41664-022-00224-0.

[13] F.R. Mansour, R.M. Abdelhameed, S.F. Hammad, I.A. Abdallah, A. Bedair, M. Locatelli, A microcrystalline cellulose/metal-organic framework hybrid for enhanced ritonavir dispersive solid phase microextraction from human plasma, Carbohydr. Polym. Technol. Appl. 7 (2024) 100453, https://doi.org/10.1016/j.carpta.2024.100453.

[14] S. Sağlam, F.N. Türk, H. Arslanoğlu, Use and applications of metal-organic frameworks (MOF) in dye adsorption: review, J. Environ. Chem. Eng. 11 (2023) 110568, https://doi.org/10.1016/j.jece.2023.110568.

[15] A. Knebel, J. Caro, Metal–organic frameworks and covalent organic frameworks as disruptive membrane materials for energy-efficient gas separation, Nat. Nanotechnol. 17 (2022) 911–923, https://doi.org/10.1038/s41565-022-01168-3.

[16] N. Király, D. Capková, R. Gyepes, N. Vargová, T. Kazda, J. Bednarčík, et al., Sr(II) and Ba(II) alkaline earth metal–organic frameworks (AE-MOFs) for selective gas adsorption, Energy Storage, and Environmental Application, Nanomaterials 13 (2023) 234, https://doi.org/10.3390/nano13020234.

[17] Y. Qin, Z. Li, Y. Duan, J. Guo, M. Zhao, Z. Tang, Nanostructural engineering of metal-organic frameworks: construction strategies and catalytic applications, Matter 5 (2022) 3260–3310, https://doi.org/10.1016/j.matt.2022.07.014.

[18] C. Duan, K. Liang, J. Lin, J. Li, L. Li, L. Kang, et al., Application of hierarchically porous metal-organic frameworks in heterogeneous catalysis: a review, Sci. China Mater. 65 (2022) 298–320, https://doi.org/10.1007/s40843-021-1910-2.

[19] D. Zhao, S. Yu, W.J. Jiang, Z.H. Cai, D.L. Li, Y.L. Liu, et al., Recent progress in metal-organic framework based fluorescent sensors for hazardous materials detection, Molecules 27 (2022) 1–33, https://doi.org/10.3390/molecules27072226.

[20] C. Huang, G. Chen, A. Nashalian, J. Chen, Advances in self-powered chemical sensing via a triboelectric nanogenerator, Nanoscale 13 (2021) 2065–2081, https://doi.org/10.1039/D0NR07770D.

[21] Y. Orooji, H. Sohrabi, N. Hemmat, F. Oroojalian, B. Baradaran, A. Mokhtarzadeh, et al., An overview on SARS-CoV-2 (COVID-19) and other human coronaviruses and their detection capability via amplification assay, chemical sensing, biosensing, immunosensing, and clinical assays, Nano-Micro Lett. 13 (2021) 18, https://doi.org/10.1007/s40820-020-00533-y.

[22] Y. Shu, Q. Ye, T. Dai, Q. Xu, X. Hu, Encapsulation of luminescent guests to construct luminescent metal–organic frameworks for chemical sensing, ACS Sens. 6 (2021) 641–658, https://doi.org/10.1021/acssensors.0c02562.

[23] B.A. Zayed, A.N. Ali, A.A. Elgebaly, N.M. Talaia, M. Hamed, F.R. Mansour, Smartphone-based point-of-care testing of the SARS-CoV-2: a systematic review, Sci. African. 21 (2023) e01757, https://doi.org/10.1016/j.sciaf.2023.e01757.

[24] D. Lou, L. Fan, T. Jiang, Y. Zhang, Advances in nanoparticle-based lateral flow immunoassay for point-of-care testing, View 3 (2022) 1–9, https://doi.org/10.1002/VIW.20200125.

[25] Z.-T. Zhong, L.-B. Song, C.-Q. Li, X. Sun, W. Chen, B. Liu, et al., Lateral flow biosensor for universal detection of various targets based on hybridization chain reaction amplification strategy with pregnancy test strip, Sensor. Actuator. B Chem. 337 (2021) 129778, https://doi.org/10.1016/j.snb.2021.129778.

[26] L. Khelifa, Y. Hu, N. Jiang, A.K. Yetisen, Lateral flow assays for hormone detection, Lab Chip 22 (2022) 2451–2475, https://doi.org/10.1039/D1LC00960E.

[27] H. Kaur, Stability testing in monoclonal antibodies, Crit. Rev. Biotechnol. 41 (2021) 692–714, https://doi.org/10.1080/07388551.2021.1874281.

[28] T.A. Shmool, L.K. Martin, L. Bui-Le, I. Moya-Ramirez, P. Kotidis, R.P. Matthews, et al., An experimental approach probing the conformational transitions and energy landscape of antibodies: a glimmer of hope for reviving lost therapeutic candidates using ionic liquid, Chem. Sci. 12 (2021) 9528–9545, https://doi.org/10.1039/D1SC02520A.

[29] I. Grunert, K. Heinrich, J. Ernst, M. Hingar, A. Briguet, M. Leiss, et al., Detailed analytical characterization of a bispecific IgG1 CrossMab antibody of the knob-into-hole format applying various stress conditions revealed pronounced stability, ACS Omega 7 (2022) 3671–3679, https://doi.org/10.1021/acsomega.1c06305.

[30] U. Ljubobratović, F. Demény, G. Peter, O. Malinovskyi, M. Kwiatkowski, B. Pataki, et al., Can artificial reproduction strategies (hormonal type and dose/thermal regime) affect gamete quality in indoor-reared pikeperch (Sander lucioperca)? Aquac. Reports. 23 (2022) 101032 https://doi.org/10.1016/j.aqrep.2022.101032.

[31] Y. Guo, Z. Han, H. Min, Z. Chen, T. Sun, L. Wang, et al., A europium-organic framework sensing material for 2-aminoacetophenone, a bacterial biomarker in water, Inorg. Chem. 60 (2021) 9192–9198, https://doi.org/10.1021/acs.inorgchem.1c01251.

[32] M. Adeel, K. Asif, M.M. Rahman, S. Daniele, V. Canzonieri, F. Rizzolio, Glucose detection devices and methods based on metal–organic frameworks and related materials, Adv. Funct. Mater. 31 (2021) 2106023, https://doi.org/10.1002/adfm.202106023.

[33] X. Wei, J. Guo, H. Lian, X. Sun, B. Liu, Cobalt metal-organic framework modified carbon cloth/paper hybrid electrochemical button-sensor for nonenzymatic glucose diagnostics, Sensor. Actuator. B Chem. 329 (2021) 129205, https://doi.org/10.1016/j.snb.2020.129205.

[34] X. He, L. Chen, X. Xiao, Y. Gan, J. Yu, J. Luo, et al., Improved utilization of Cu0 for efficient adsorption of iodine in gas and solution by mesoporous Cu0-SBA-15 via solvothermal reduction method, Chem. Eng. J. 462 (2023) 142175, https://doi.org/10.1016/j.cej.2023.142175.

[35] N. Stock, S. Biswas, Synthesis of metal-organic frameworks (MOFs): routes to various MOF topologies, morphologies, and composites, Chem. Rev. 112 (2012) 933–969, https://doi.org/10.1021/cr200304e.

[36] Y. Lee, J. Kim, W. Ahn, Synthesis of metal-organic frameworks: a mini review, Kor. J. Chem. Eng. 30 (2013) 1667–1680, https://doi.org/10.1007/s11814-013-0140-6.

[37] U. Mueller, M. Schubert, F. Teich, H. Puetter, K. Schierle-Arndt, J. Pastré, Metal–organic frameworks—prospective industrial applications, J. Mater. Chem. 16 (2006) 626–636, https://doi.org/10.1039/B511962F.

[38] J.F. Fernández-Bertran, Mechanochemistry: an overview, Pure Appl. Chem. 71 (1999) 581–586, https://doi.org/10.1351/pac199971040581.

[39] G. Kaupp, Mechanochemistry: the varied applications of mechanical bond-breaking, CrystEngComm 11 (2009) 388–403, https://doi.org/10.1039/b810822f.

[40] A.L. Garay, A. Pichon, S.L. James, Solvent-free synthesis of metal complexes, Chem. Soc. Rev. 36 (2007) 846, https://doi.org/10.1039/b600363j.

[41] M.K. Beyer, H. Clausen-Schaumann, Mechanochemistry: the mechanical activation of covalent bonds, Chem. Rev. 105 (2005) 2921–2948, https://doi.org/10.1021/cr030697h.

[42] M. Salehipour, S. Rezaei, M. Rezaei, M. Yazdani, M. Mogharabi-Manzari, Opportunities and challenges in biomedical applications of metal–organic frameworks, J. Inorg. Organomet. Polym. Mater. 31 (2021) 4443–4462, https://doi.org/10.1007/s10904-021-02118-7.

[43] L.J. Han, D. Zheng, S.G. Chen, H.G. Zheng, J. Ma, A highly solvent-stable metal–organic framework nanosheet: morphology control, exfoliation, and luminescent property, Small 14 (2018) 1–7, https://doi.org/10.1002/smll.201703873.

[44] O.K. Farha, I. Eryazici, N.C. Jeong, B.G. Hauser, C.E. Wilmer, A.A. Sarjeant, et al., Metal–organic framework materials with ultrahigh surface areas: is the sky the limit? J. Am. Chem. Soc. 134 (2012) 15016–15021, https://doi.org/10.1021/ja3055639.

[45] X. Gong, H. Noh, N.C. Gianneschi, O.K. Farha, Interrogating kinetic versus thermodynamic topologies of metal–organic frameworks via combined transmission electron microscopy and X-ray diffraction analysis, J. Am. Chem. Soc. 141 (2019) 6146–6151, https://doi.org/10.1021/jacs.9b01789.

[46] C. Eames, J.M. Frost, P.R.F. Barnes, B.C. O'Regan, A. Walsh, M.S. Islam, Ionic transport in hybrid lead iodide perovskite solar cells, Nat. Commun. 6 (2015) 2–9, https://doi.org/10.1038/ncomms8497.

[47] A.J. Rossini, A. Zagdoun, M. Lelli, J. Canivet, S. Aguado, O. Ouari, et al., Dynamic nuclear polarization enhanced solid-state NMR spectroscopy of functionalized metal-organic frameworks, Angew. Chem. Int. Ed. 51 (2012) 123–127, https://doi.org/10.1002/anie.201106030.

[48] E. Brunner, M. Rauche, Solid-state NMR spectroscopy: an advancing tool to analyse the structure and properties of metal-organic frameworks, Chem. Sci. 11 (2020) 4297–4304, https://doi.org/10.1039/d0sc00735h.

[49] K. Chakarova, I. Strauss, M. Mihaylov, N. Drenchev, K. Hadjiivanov, Evolution of acid and basic sites in UiO-66 and UiO-66-NH2 metal-organic frameworks: FTIR study by probe molecules, Microporous Mesoporous Mater. 281 (2019) 110–122, https://doi.org/10.1016/j.micromeso.2019.03.006.

[50] S.G. Kozlova, M.R. Ryzhikov, D.G. Samsonenko, A.V. Kalinkin, Interatomic interactions in M2(C8H4O4)2C6H12N2 (M = Zn, Cu, Co, Ni) metal-organic framework polymers: X-ray photoelectron spectroscopy, QTAIM and ELF study, J. Mol. Struct. 1150 (2017) 268–273, https://doi.org/10.1016/j.molstruc.2017.08.077.

[51] C.S. Tsao, M.S. Yu, T.Y. Chung, H.C. Wu, C.Y. Wang, K. Sen Chang, et al., Characterization of pore structure in metal-organic framework by small-angle X-ray scattering, J. Am. Chem. Soc. 129 (2007) 15997–16004, https://doi.org/10.1021/ja0752336.

[52] A. Karmakar, P. Samanta, S. Dutta, S.K. Ghosh, Fluorescent "turn-on" sensing based on metal–organic frameworks (MOFs), Chem. Asian J. 14 (2019) 4506–4519, https://doi.org/10.1002/asia.201901168.

[53] J. Dong, D. Zhao, Y. Lu, W.Y. Sun, Photoluminescent metal-organic frameworks and their application for sensing biomolecules, J. Mater. Chem. A 7 (2019) 22744–22767, https://doi.org/10.1039/c9ta07022b.

[54] H.L. Xu, X.S. Zeng, J. Li, Y.C. Xu, H.J. Qiu, D.R. Xiao, The impact of metal ions on photoinduced electron-transfer properties: four photochromic metal-organic frameworks based on a naphthalenediimide chromophore, CrystEngComm 20 (2018) 2430–2439, https://doi.org/10.1039/c8ce00213d.

[55] A.J. Howarth, Y. Liu, P. Li, Z. Li, T.C. Wang, J.T. Hupp, et al., Chemical, thermal and mechanical stabilities of metal–organic frameworks, Nat. Rev. Mater. 1 (2016) 15018, https://doi.org/10.1038/natrevmats.2015.18.

[56] J.-K. Sun, Q. Xu, Functional materials derived from open framework templates/precursors: synthesis and applications, Energy Environ. Sci. 7 (2014) 2071, https://doi.org/10.1039/c4ee00517a.

[57] Y. Fujiwara, S. Horike, K. Kongpatpanich, T. Sugiyama, N. Tobori, H. Nishihara, et al., Control of pore distribution of porous carbons derived from Mg 2+ porous coordination polymers, Inorg. Chem. Front. 2 (2015) 473–476, https://doi.org/10.1039/C5QI00019J.

[58] S.K. Henninger, F. Jeremias, H. Kummer, C. Janiak, MOFs for use in adsorption heat pump processes, Eur. J. Inorg. Chem. 2012 (2012) 2625–2634, https://doi.org/10.1002/ejic.201101056.

[59] P. Nugent, Y. Belmabkhout, S.D. Burd, A.J. Cairns, R. Luebke, K. Forrest, et al., Porous materials with optimal adsorption thermodynamics and kinetics for CO2 separation, Nature 495 (2013) 80–84, https://doi.org/10.1038/nature11893.

[60] R.A. Peralta, B. Alcántar-Vázquez, M. Sánchez-Serratos, E. González-Zamora, I. A. Ibarra, Carbon dioxide capture in the presence of water vapour in InOF-1, Inorg. Chem. Front. 2 (2015) 898–903, https://doi.org/10.1039/C5QI00077G.

[61] J.C. Tan, A.K. Cheetham, Mechanical properties of hybrid inorganic–organic framework materials: establishing fundamental structure–property relationships, Chem. Soc. Rev. 40 (2011) 1059–1080, https://doi.org/10.1039/c0cs00163e.

[62] A.D. Katsenis, A. Puškarić, V. Štrukil, C. Mottillo, P.A. Julien, K. Užarević, et al., In situ X-ray diffraction monitoring of a mechanochemical reaction reveals a unique topology metal-organic framework, Nat. Commun. 6 (2015) 6662, https://doi.org/10.1038/ncomms7662.

[63] F.-X. Coudert, Responsive metal–organic frameworks and framework materials: under pressure, taking the heat, in the spotlight, with friends, Chem. Mater. 27 (2015) 1905–1916, https://doi.org/10.1021/acs.chemmater.5b00046.

[64] W. Li, S. Henke, A.K. Cheetham, Research Update: mechanical properties of metal-organic frameworks – influence of structure and chemical bonding, Apl. Mater. 2 (2014) 123902, https://doi.org/10.1063/1.4904966.

[65] A. Bedair, K. Okasha, F.R. Mansour, Spectroscopic methods for COVID-19 detection and early diagnosis, Virol. J. 19 (2022) 152, https://doi.org/10.1186/s12985-022-01867-2.

[66] S. Afreen, Z. He, Y. Xiao, J.-J. Zhu, Nanoscale metal–organic frameworks in detecting cancer biomarkers, J. Mater. Chem. B 8 (2020) 1338–1349, https://doi.org/10.1039/C9TB02579K.

[67] V. Aggarwal, S. Solanki, B.D. Malhotra, Applications of metal-organic framework-based bioelectrodes, Chem. Sci. 13 (2022) 8727–8743, https://doi.org/10.1039/d2sc03441g.

[68] S. Jain, M. Nehra, R. Kumar, N. Dilbaghi, T. Hu, S. Kumar, et al., Internet of medical things (IoMT)-integrated biosensors for point-of-care testing of infectious diseases, Biosens. Bioelectron. 179 (2021) 113074, https://doi.org/10.1016/j.bios.2021.113074.

[69] M. Alafeef, P. Moitra, K. Dighe, D. Pan, RNA-extraction-free nano-amplified colorimetric test for point-of-care clinical diagnosis of COVID-19, Nat. Protoc. 16 (2021) 3141–3162, https://doi.org/10.1038/s41596-021-00546-w.

[70] M.H. Choi, G.S.R. Kumara, J. Lee, Y.J. Seo, Point-of-care COVID-19 testing: colorimetric diagnosis using rapid and ultra-sensitive ramified rolling circle amplification, Anal. Bioanal. Chem. 414 (2022) 5907–5915, https://doi.org/10.1007/s00216-022-04156-7.

[71] Y. Tsao, C. Yang, Y. Wen, T. Chang, K. Matsuura, Y. Chen, et al., Point-of-care semen analysis of patients with infertility via smartphone and colorimetric paper-based diagnostic device, Bioeng. Transl. Med. 6 (2021) 1–11, https://doi.org/10.1002/btm2.10176.

[72] B. Alsaeed, F.R. Mansour, Distance-based paper microfluidics; principle, technical aspects and applications, Microchem. J. 155 (2020) 104664, https://doi.org/10.1016/j.microc.2020.104664.

[73] X. Luan, Y. Pan, D. Zhou, B. He, X. Liu, Y. Gao, et al., Cerium metal organic framework mediated molecular threading for point-of-care colorimetric assays, Biosens. Bioelectron. (2020) 112406, https://doi.org/10.1016/j.bios.2020.112406.

[74] K. Ge, X. He, Z. Xu, R. Chu, A luminescent lanthanide-functionalized metal-organic framework as a highly selective and sensitive chemical sensor for dopamine, ChemistrySelect 4 (2019) 12573–12579, https://doi.org/10.1002/slct.201903609.

[75] L. Yu, L. Feng, L. Xiong, S. Li, Q. Xu, X. Pan, et al., Paper microchip for visual dopamine assay, Nanoscale (2021) 11188–11196, https://doi.org/10.1039/d1nr02036f.

[76] Y. Cai, Y. Hua, M. Yin, H. Liu, S. Li, F. Wang, et al., Sensors and Actuators B : chemical Fabrication of test strips with gold-silver nanospheres and metal – organic frameworks : a fl uorimetric method for sensing trace cysteine in hela cells, Sensor. Actuator. B Chem. 302 (2020) 127198, https://doi.org/10.1016/j.snb.2019.127198.

[77] Y. Zeng, M. Wang, Z. Sun, Metal – Organic Framework Nanosheets as Enzyme Mimics for the Detection of Protein Biomarkers †, 2022, pp. 450–455, https://doi.org/10.1039/d1tb02192c.

[78] S. Reyes, E. Rizzo, A. Ting, E. Dikici, S.K. Deo, Sensors & Diagnostics Metal organic framework encapsulated tamavidin- Gluc reporter : application in COVID-19 spike antigen bioluminescent immunoassay, Sensors and Diagnostics (2022) 1198–1208, https://doi.org/10.1039/d2sd00145d.

[79] Y. Shu, T. Dai, Q. Ye, D. Jin, Q. Xu, X. Hu, A dual-emitting two-dimensional nickel-based metal-organic framework nanosheets: Eu3+/Ag+ functionalization synthesis and ratiometric sensing in aqueous solution, J. Fluoresc. 31 (2021) 1947–1957, https://doi.org/10.1007/s10895-021-02826-w.

[80] H.A.J. Al Lawati, J. Hassanzadeh, Analytica Chimica Acta Dual-function 2D cobalt metal-organic framework embedded on paper as a point-of-care diagnostic device : application for the quanti fi cation of glucose, Anal. Chim. Acta 1139 (2020) 15–26, https://doi.org/10.1016/j.aca.2020.09.026.

[81] Y. Zhang, B. Yan, A point-of-care diagnostics logic detector based on glucose oxidase immobilized lanthanide functionalized metal-organic frameworks, Nanoscale 11 (2019) 22946–22953, https://doi.org/10.1039/c9nr06475c.

[82] L. Xiong, L. Yu, Multifunctional Lanthanide Metal-Organic Framework Based Ratiometric Fluorescence Visual Detection Platform for Alkaline Phosphatase Activity, 2021.

[83] S. Choi, M. Dickson, J. Yu, Chem Soc Rev Developing Luminescent Silver Nanodots for Biological Applications, 2012, pp. 1867–1891, https://doi.org/10.1039/c1cs15226b.

[84] F. Caruso, T. Hyeon, V. Rotello, H. Jans, Nanomedicine Themed Issue, 2012, https://doi.org/10.1039/c1cs15280g.

[85] Y. Lu, W. Chen, Chem Soc Rev Sub-nanometre sized metal clusters : from synthetic challenges to the unique property discoveries, Chem. Soc. Rev. 41 (2012), https://doi.org/10.1039/c2cs15325d.

[86] C. Fan, X. Lv, F. Liu, L. Feng, M. Liu, Y. Cai, et al., Silver nanoclusters encapsulated into metal – organic frameworks with enhanced fluorescence and specific ion accumulation towards the microdots array-based fluorimetric analysis of copper in blood Silver nanoclusters encapsulated into metal – organic fram, ACS Sens. (2018), https://doi.org/10.1021/acssensors.7b00874.

[87] L. Feng, M. Liu, H. Liu, C. Fan, Y. Cai, L. Chen, et al., High-throughput and sensitive fluorimetric strategy for MicroRNAs in blood using wettable microwells array and silver nanoclusters with red fluorescence enhanced by metal organic frameworks, ACS Appl. Mater. Interfaces 10 (2018) 23647–23656, https://doi.org/10.1021/acsami.8b07137.

[88] L. Wei, Y. Lei, H. Fu, J. Yao, Fullerene hollow microspheres prepared by bubble-templates as sensitive and selective electrocatalytic sensor for biomolecules, ACS Appl. Mater. Interfaces 4 (2012) 1594–1600, https://doi.org/10.1021/am201769u.

[89] D.W. Kimmel, G. Leblanc, M.E. Meschievitz, D.E. Cliffel, Electrochemical sensors and biosensors, Anal. Chem. 84 (2012) 685–707, https://doi.org/10.1021/ac202878q.

[90] R. Sharma, K.V. Ragavan, M.S. Thakur, K.S.M.S. Raghavarao, Recent advances in nanoparticle based aptasensors for food contaminants, Biosens. Bioelectron. 74 (2015) 612–627, https://doi.org/10.1016/j.bios.2015.07.017.

[91] X. Lin, Y. Wang, M. Zou, T. Lan, Y. Ni, Electrochemical non-enzymatic glucose sensors based on nano-composite of Co3O4 and multiwalled carbon nanotube, Chin. Chem. Lett. 30 (2019) 1157–1160, https://doi.org/10.1016/j.cclet.2019.04.009.

[92] M. Li, S. Mao, S. Wang, H.F. Li, J.M. Lin, Chip-based SALDI-MS for rapid determination of intracellular ratios of glutathione to glutathione disulfide, Sci. China Chem. 62 (2019) 142–150, https://doi.org/10.1007/s11426-018-9327-7.

[93] L. Zhang, W. Yang, Y. Yang, H. Liu, Z. Gu, Smartphone-based point-of-care testing of salivary α-amylase for personal psychological measurement, Analyst 140 (2015) 7399–7406, https://doi.org/10.1039/c5an01664a.

[94] H. Li, X. Liu, L. Li, X. Mu, R. Genov, A.J. Mason, CMOS electrochemical instrumentation for biosensor microsystems: a review, Sensors (2017) 17, https://doi.org/10.3390/s17010074.

[95] S.I. Kaya, L. Karadurmus, G. Ozcelikay, N.K. Bakirhan, S.A. Ozkan, Electrochemical Virus Detections with Nanobiosensors, INC, 2020, https://doi.org/10.1016/B978-0-12-819870-4.00017-7.

[96] S. Lv, K. Zhang, L. Zhu, D. Tang, R. Niessner, D. Knopp, H2-Based electrochemical biosensor with Pd Nanowires@ZIF-67 molecular sieve bilayered sensing interface for immunoassay, Anal. Chem. 91 (2019) 12055–12062, https://doi.org/10.1021/acs.analchem.9b03177.

[97] S. Lv, K. Zhang, Q. Zhou, D. Tang, Plasmonic enhanced photoelectrochemical aptasensor with D-A F8BT/g-C3N4 heterojunction and AuNPs on a 3D-printed device, Sensor. Actuator. B Chem. 310 (2020) 127874, https://doi.org/10.1016/j.snb.2020.127874.

[98] S. Lv, K. Zhang, L. Zhu, D. Tang, Zif-8-assisted nayf4:yb,tm@zno converter with exonuclease iii-powered dna walker for near-infrared light responsive biosensor, Anal. Chem. 92 (2020) 1470–1476, https://doi.org/10.1021/acs.analchem.9b04710.

[99] S.F. Hammad, I.A. Abdallah, A. Bedair, R.M. Abdelhameed, M. Locatelli, F. R. Mansour, Metal organic framework-derived carbon nanomaterials and MOF hybrids for chemical sensing, TrAC, Trends Anal. Chem. (2023) 117425, https://doi.org/10.1016/j.trac.2023.117425.

[100] M. Ding, X. Cai, H.L. Jiang, Improving MOF stability: approaches and applications, Chem. Sci. 10 (2019) 10209–10230, https://doi.org/10.1039/c9sc03916c.

[101] S. Lv, Y. Tang, K. Zhang, D. Tang, Wet NH3-triggered NH2-MIL-125(Ti) structural switch for visible fluorescence immunoassay impregnated on paper, Anal. Chem. 90 (2018) 14121–14125, https://doi.org/10.1021/acs.analchem.8b04981.

[102] R. Ren, G. Cai, Z. Yu, Y. Zeng, D. Tang, Metal-polydopamine framework: an innovative signal-generation tag for colorimetric immunoassay, Anal. Chem. 90 (2018) 11099–11105, https://doi.org/10.1021/acs.analchem.8b03538.

[103] H.A. Schulze, B. Hoppe, M. Schäfer, D.P. Warwas, P. Behrens, Electrically conducting nanocomposites of carbon nanotubes and metal-organic frameworks with strong interactions between the two components, ChemNanoMat 5 (2019) 1159–1169, https://doi.org/10.1002/cnma.201900110.

[104] A. Amini, S. Kazemi, V. Safarifard, Metal-organic framework-based nanocomposites for sensing applications – a review, Polyhedron 177 (2020) 114260, https://doi.org/10.1016/j.poly.2019.114260.

[105] Q. Wang, Z.-H. Ren, W.-M. Zhao, L. Wang, X. Yan, A. Zhu, et al., Research advances on surface plasmon resonance biosensors, Nanoscale 14 (2022) 564–591, https://doi.org/10.1039/D1NR05400G.

[106] A. Philip, A.R. Kumar, The performance enhancement of surface plasmon resonance optical sensors using nanomaterials: a review, Coord. Chem. Rev. 458 (2022) 214424, https://doi.org/10.1016/j.ccr.2022.214424.

[107] A.G. Brolo, Plasmonics for future biosensors, Nat. Photonics 6 (2012) 709–713, https://doi.org/10.1038/nphoton.2012.266.

[108] J.R. Mejía-Salazar, O.N. Oliveira, Plasmonic Biosensing, Chem. Rev. 118 (2018) 10617–10625, https://doi.org/10.1021/acs.chemrev.8b00359.

[109] A.J. Johnson, D.A. Martin, N. Karabatsos, J.T. Roehrig, Detection of anti-arboviral immunoglobulin G by using a monoclonal antibody-based capture enzyme-linked immunosorbent assay, J. Clin. Microbiol. 38 (2000) 1827–1831, https://doi.org/10.1128/JCM.38.5.1827-1831.2000.

[110] R.L. Ashley, J. Militoni, F. Lee, A. Nahmias, L. Corey, Comparison of Western blot (immunoblot) and glycoprotein G-specific immunodot enzyme assay for detecting antibodies to herpes simplex virus types 1 and 2 in human sera, J. Clin. Microbiol. 26 (1988) 662–667, https://doi.org/10.1128/jcm.26.4.662-667.1988.

[111] R. Scully, J. Chen, A. Plug, Y. Xiao, D. Weaver, J. Feunteun, et al., Association of BRCA1 with Rad51 in mitotic and meiotic cells, Cell 88 (1997) 265–275, https://doi.org/10.1016/S0092-8674(00)81847-4.

[112] J.C. Vidal, L. Bonel, A. Ezquerra, S. Hernández, J.R. Bertolín, C. Cubel, et al., Electrochemical affinity biosensors for detection of mycotoxins: a review, Biosens. Bioelectron. 49 (2013) 146–158, https://doi.org/10.1016/j.bios.2013.05.008.

[113] E. Ng, K.C. Nadeau, S.X. Wang, Giant magnetoresistive sensor array for sensitive and specific multiplexed food allergen detection, Biosens. Bioelectron. 80 (2016) 359–365, https://doi.org/10.1016/j.bios.2016.02.002.

[114] T. Endo, K. Kerman, N. Nagatani, H.M. Hiepa, D.K. Kim, Y. Yonezawa, et al., Multiple label-free detection of antigen-antibody reaction using localized surface plasmon resonance-based core-shell structured nanoparticle layer nanochip, Anal. Chem. 78 (2006) 6465–6475, https://doi.org/10.1021/ac0608321.

[115] C. Wang, J. Luan, S. Tadepalli, K.-K. Liu, J.J. Morrissey, E.D. Kharasch, et al., Silk-encapsulated plasmonic biochips with enhanced thermal stability, ACS Appl. Mater. Interfaces 8 (2016) 26493–26500, https://doi.org/10.1021/acsami.6b07362.

[116] K. Liang, R. Ricco, C.M. Doherty, M.J. Styles, S. Bell, N. Kirby, et al., Biomimetic mineralization of metal-organic frameworks as protective coatings for biomacromolecules, Nat. Commun. 6 (2015) 7240, https://doi.org/10.1038/ncomms8240.

[117] G. Zheng, S. de Marchi, V. López-Puente, K. Sentosun, L. Polavarapu, I. Pérez-Juste, et al., Encapsulation of single plasmonic nanoparticles within ZIF-8 and SERS analysis of the MOF flexibility, Small (2016) 3935–3943, https://doi.org/10.1002/smll.201600947.

[118] C. Wang, S. Tadepalli, J. Luan, K.K. Liu, J.J. Morrissey, E.D. Kharasch, et al., Metal-organic framework as a protective coating for biodiagnostic chips, Adv. Mater. 29 (2017), https://doi.org/10.1002/adma.201604433.

[119] S. Luo, A. Mancini, E. Lian, W. Xu, R. Berté, Y. Li, Large area patterning of highly reproducible and sensitive SERS sensors based on 10-nm annular gap arrays, Nanomaterials 12 (2022), https://doi.org/10.3390/nano12213842.

[120] C. Wang, L. Wang, S. Tadepalli, J.J. Morrissey, E.D. Kharasch, R.R. Naik, et al., Ultrarobust biochips with metal-organic framework coating for point-of-care diagnosis, ACS Sens. 3 (2018) 342–351, https://doi.org/10.1021/acssensors.7b00762.

[121] V. Greco, A. Giuffrida, M. Locatelli, F. Savini, U. de Grazia, L. Ciriolo, et al., Emerging procedures and solvents in biological sample pre-treatment, Adv. Sample Prep. 6 (2023) 100066, https://doi.org/10.1016/j.sampre.2023.100066.

[122] M. Locatelli, A. Kabir, M. Perrucci, S. Ulusoy, H.I. Ulusoy, I. Ali, Green profile tools: current status and future perspectives, Adv. Sample Prep. 6 (2023) 100068, https://doi.org/10.1016/j.sampre.2023.100068.

[123] Á.I. López-Lorente, F. Pena-Pereira, S. Pedersen-Bjergaard, V.G. Zuin, S.A. Ozkan, E. Psillakis, The ten principles of green sample preparation, TrAC, Trends Anal. Chem. 148 (2022) 116530, https://doi.org/10.1016/j.trac.2022.116530.

[124] T. Yan, G. Zhang, H. Chai, L. Qu, X. Zhang, Flexible biosensors based on colorimetry, fluorescence, and electrochemistry for point-of-care testing, Front. Bioeng. Biotechnol. 9 (2021) 1–11, https://doi.org/10.3389/fbioe.2021.753692.