

Recent advances in portable devices for environmental monitoring applications

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ABSTRACT

Environmental pollution remains a major societal problem, leading to serious impacts on living organisms including humans. Human activities such as civilization, urbanization, and industrialization are major causes of pollution. Imposing stricter rules helps control environmental pollutant levels, creating a need for reliable pollutant monitoring in air, water, and soil. The application of traditional analytical techniques is limited in low-resource areas because they are sophisticated, expensive, and bulky. With the development of biosensors and microfluidics technology, environmental monitoring has significantly improved the analysis time, low cost, portability, and ease of use. This review discusses the fundamentals of portable devices, including microfluidics and biosensors, for environmental control. Recently, publications reviewing microfluidics and biosensor device applications have increased more than tenfold, showing the potential of emerging novel approaches for environmental monitoring. Strategies for enzyme-, immunoassay-, and molecular-based analyte sensing are discussed based on their mechanisms and applications. Microfluidic and biosensor platforms for detecting major pollutants, including metal ions, pathogens, pesticides, and antibiotic residues, are reviewed based on their working principles, advantages, and disadvantages. Challenges and future trends for the device design and fabrication process to improve performance are discussed. Miniaturization, low cost, selectivity, sensitivity, high automation, and savings in samples and reagents make the devices ideal alternatives for in-field detection, especially in low-resource areas. However, their operation with complicated environmental samples requires further research to improve the specificity and sensitivity. Although there is a wide range of devices available for environmental applications, their implementation in real-world situations is limited. This study provides insights into existing issues that can be used as references and a comparative analysis for future studies and applications.

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I. INTRODUCTION

Environmental pollution caused by extreme industrial development, rapid population growth, and urbanization has become a global concern in the modern world. The increasing release and accumulation of various types of contaminants into the surrounding environment have greatly impacted human health and ecosystems.^{1–4} Hazardous substances from both human and natural sources enter

the environment through human activities and are considered to be environmental pollutants. These substances include chemical compounds such as pesticides, metals, antibiotics, and physical, radiological, or biological agents such as microorganisms, mites, and allergic agents.^{5,6} Therefore, monitoring environmental pollutants is crucial for controlling their potential harm to humans, flora, and fauna. Various technologies have been employed for environmental

detection, monitoring, and remediation. Classical spectroscopic and chromatographic methods are typically used for the detection of environmental pollutants. However, these methods are laborious and require complicated analyses with high costs and a lengthy analysis time.^{7–9} Therefore, there is an urgent need for rapid, sensitive, accurate, simple, and cost-effective tools to screen for pollutants.

The past decades have seen the rapid development of portable devices, such as biosensors and microfluidic devices, for various applications. Biosensors are valuable tools for simple, rapid, and on-site detection. Biosensors consist of biomolecule recognition elements, including enzymes, cell receptors, or antibodies for sensing targets, and a bio-transducer for signal acquisition.¹⁰ Microfluidic systems are based on the microscale laminar fluid flow for analytical applications. They are advantageous for analytical applications because they require small amounts of samples and reagents with a rapid analysis time, high sensitivity, and simplicity.^{11–13} Owing to their large surface-to-volume ratios, microfluidic devices manipulate fluid flow inside microchannels and chamber systems to achieve rapid and sensitive reactions with a low consumption of reagents and samples.

Analytical processes are typically performed in laboratories and require trained personnel. With the aid of portable biosensing devices, such as microfluidic devices and biosensors, analytical procedures can be integrated into a miniature chip. For environmental monitoring, sample sizes are typically very large. Moreover, the conventional methods for sample preparation and analysis are expensive and time-consuming. Alternatively, portable biosensing devices enable the rapid handling of bulky environmental samples with high simplicity and sensitivity for the on-site detection of pollutants, such as pesticides, heavy metals, waterborne bacteria, or toxic gases.¹⁴ The complexity of environmental samples must be considered when developing biosensors and microfluidic devices. While the applications of microfluidic devices and biosensors are more common in the field of biomedical or food technology, such as diagnostics and quality control, their applications have also been extended to monitor environmental pollutants, such as herbicides and pesticides in soil, heavy metals in soil and water, waterborne pathogens in drinking water, and toxic gases and pollutants in industrial effluents.

In this review, the major types of biosensors and microfluidic devices are summarized and their applications in environmental monitoring are explored. First, the urgency of environmental pollution control and the limitations of conventional detection methods are discussed. Second, the fundamentals of microfluidics and biosensors are reviewed to provide an overview of the techniques used. Finally, the applications of microfluidics and biosensors for monitoring environmental pollutants, including heavy metals, pesticides, and pathogens, are presented and analyzed. This study highlights the potential challenges and future perspectives on portable biosensing devices for environmental monitoring.

II. BIOSENSOR IN ENVIRONMENTAL MONITORING

Biosensors consist of biorecognition elements and signal transducers that produce detectable or measurable signals when monitoring analytes and are advanced analytical devices for detecting environmental pollutants. Biosensors can be classified based on the biorecognition principle or the transduction methods used. Biosensors can be further categorized as enzyme-, antibody-, aptamer-, and whole-cell-based.

A. Enzyme-based biosensor

Enzyme-based biosensors employ enzymes as the sensing elements for target recognition. Enzymes are common biological catalysts that enhance the reaction rates. This enzymatic reaction generates a signal upon target recognition, which is then converted into a measurable response using a transducer. Enzyme-based biosensors have gained considerable attention for environmental monitoring because of their high sensitivity and specificity. Many possible mechanisms are involved in target sensing using enzyme-based biosensors, including analyte metabolism, activation, inhibition, and alteration of enzymes by analytes (Fig. 1).¹⁵ In the analyte metabolism, the concentration of the analytes can be measured by monitoring their catalytic transformations. In some cases, analytes play important roles, such as activation or inhibition agents for enzymes; therefore, the concentration of analytes can be determined by the products catalyzed by enzymatic reactions. Some analytes alter the characteristics of enzymes; therefore, tracking the alteration of enzymes is a possible method for measuring analytes.^{16,17} Although enzyme-based biosensors are commonly used and have many advantages, their performance can be limited owing to the susceptibility of enzymes to unfavorable conditions, such as pH, temperature, and inhibitors.

B. Antibody-based biosensor

The antibody recognizes and binds specifically to the antigens, resulting in the formation of stable antibody–antigens. Antibodies are widely used as sensitive and specific sensing elements in biosensors for the detection of environmental pollutants. Antibody-based biosensors can be categorized into two classes: nonlabeled and labeled. In the non-labeled class, physical changes caused by antibody–antigen interactions are measured directly. In the labeled class, sensitive and detectable markers are employed to assess the antibody–antigen complex.^{18,19} Various compounds can be used as markers, including fluorescent dyes, enzymes, and nanoparticles, as shown in Fig. 2.¹⁸ Antibody-based biosensors have many advantages, including simplicity, high sensitivity, and specificity. However, the performance of antibody-based biosensors significantly depends on the immobilization strategy of the antibody on the sensor surface. Therefore, an immobilization strategy that does not alter the specificity, immunological activity, and limit of detection (LOD) is crucial for sensor development.¹⁹

C. Aptamer-based biosensor

Aptamers are single-stranded oligonucleotides that form complexes with targets with strong affinity and high specificity. Aptamers possess unique structures that help them interact with a wide range of targets, from small molecules to macromolecules, and even whole microorganisms.²⁰ Figure 3 illustrates the fabrication process and sensing principle of the thiamethoxam (TMX) electrochemical aptasensor. Aptamers are widely used in biosensors owing to their many advantages. First, aptamer-based biosensors are stable under many storage conditions because of the natural characteristics of nucleic acids. Second, aptamers are chemically synthesized and modified for the detection of target molecules.²¹ An internal-standard-based surface-enhanced Raman scattering

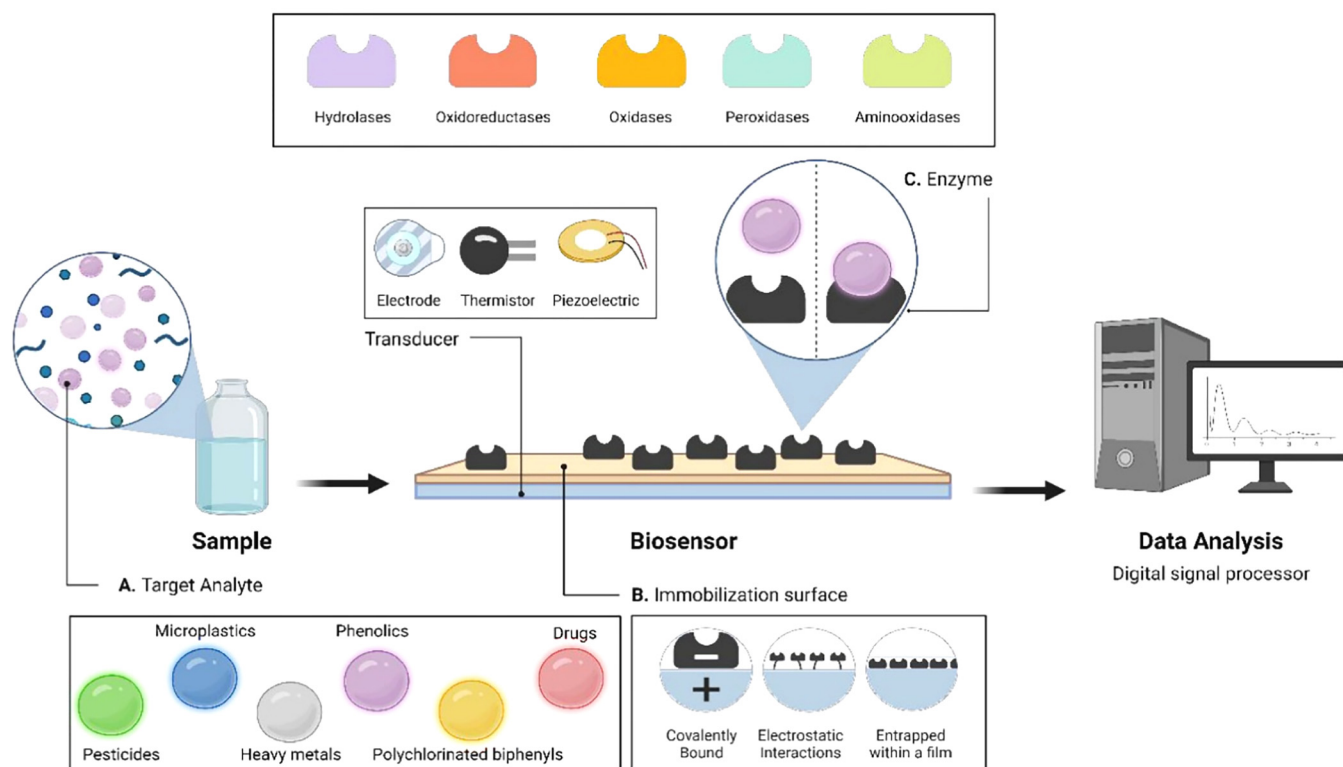


FIG. 1. A schematic illustration showing an overview of the enzyme-based biosensors for environmental applications, including a transducer, biological receptor, and a matrix or immobilization surface. Reprinted with permission from González-González *et al.*, *Ind. Eng. Chem. Res.* **62**(11), 4503–4520 (2023). Copyright (2023) American Chemical Society.¹⁵

(SERS) aptasensor has been proposed to quantitatively detect silver ions in environmental samples.²² This method offers a simple and sensitive approach to detect heavy metals with a limit of detection (LOD) of 50 pM. A sulfur-doped graphene quantum-dot-based fluorescent turn-on aptasensor has been developed to detect the pesticide omethoate in environmental samples.²³ The aptasensor achieved ultrasensitive detection with a LOD of 0.001 ppm and high specificity over other pesticides. However, the applications of aptamer-based biosensors are limited for several reasons. First, *in vivo* environmental factors, such as nucleases, can affect the activity of aptamers. Second, aptamer synthesis methods are usually costly, time-consuming, and low efficiency.^{24,25}

D. Whole-cell-based biosensor

Whole-cell biosensors are formed from cells and tissues. Whole cells and tissues are potential biosensors that can recognize a wide range of analytes and generate detectable signals. The cells can self-replicate and produce biorecognitive elements, such as enzymes and antibodies, for direct sensing without the need for the purification of the sensing elements, as shown in Fig. 4.²⁶ Owing to their high specificity, sensitivity, and LOD, whole-cell-based biosensors have been successfully used to monitor environmental

pollutants.²⁶ Many studies have developed whole-cell-based biosensors for monitoring various pollutants such as heavy metals and herbicides. A microbial biosensor has been developed to detect heavy metals such as Pb^{2+} with a rapid reaction time, high portability, sensitivity, stability, and low cost.²⁷ A microbial amperometric biosensor has been proposed to detect herbicide online.²⁸ The device was constructed using the cyanobacteria *Anabaena variabilis*. Whole-cell-based biosensors have many advantages; however, their applications are limited. The complicated matrix of real environmental samples can interfere with device performance. Moreover, toxic compounds in the samples limit the cell types that can be selected to develop the sensor.²⁹

In summary, well-documented reports have demonstrated the practical approaches of biosensors for the detection of polluting elements in environmental monitoring, including heavy metals, organic pollutants, and wastewater quality. Specific binding sites for DNA probes, such as guanine-rich probes and whole-cell biosensors, have been employed in environmental purity tracking because of the formation of stable complex structures and microbial whole-cell genetic expression in response to contaminating chemicals.^{30,31} Additionally, diverse polluting organic particles in soil and water can be detected using enzymes, aptamers, and whole-cell biosensors.^{32–34}

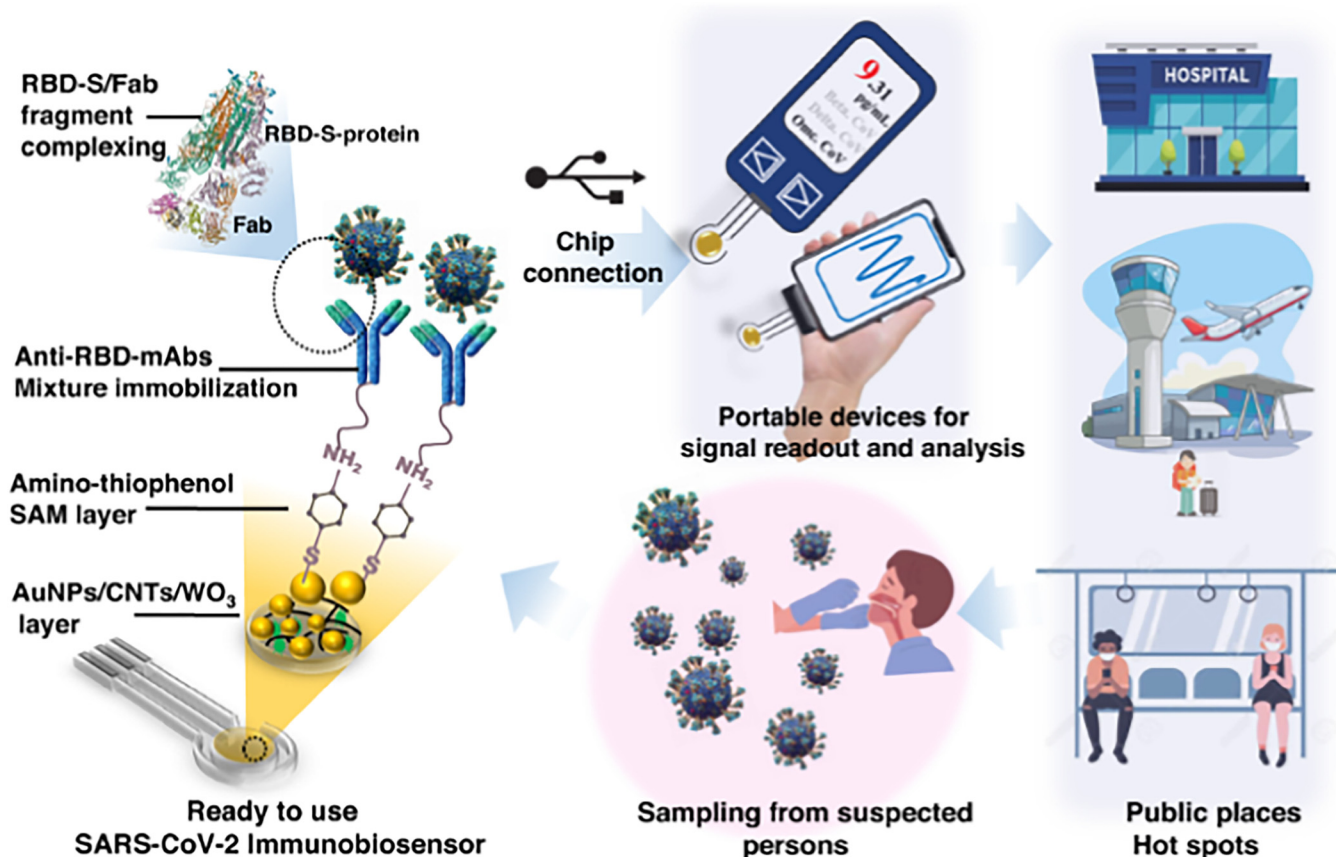


FIG. 2. A schematic illustration showing a novel double-antibody-based immunobiosensor chip for SARS-CoV-2 analysis. Reprinted with permission from Hussein *et al.*, *Microsyst. Nanoeng.* **9**, 105 (2023). Copyright (2022) Springer Nature.¹⁸

Microbial fuel cells (MFCs) are an emerging technology for generating electricity from renewable biomass. Due to their significant advantages, including simple construction and operation, *in situ* monitoring, and low cost, MFCs are considered a promising tool for environmental monitoring using whole-cell-based biosensors. MFC-based biosensors have been employed to monitor various environmental factors, including biochemical oxygen demand, dissolved oxygen, chemical oxygen demand, volatile fatty acids, and microbial activity.³⁵ The heavy-metal concentration and chemical oxygen demand in wastewater can be observed using MFC-based biosensors.^{36–38} Fluorescence resonance energy transfer (FRET) is a common detection method for nanomaterial sensors that use linked emission molecules and biomolecules (enzymes and aptamers). In addition to organic nanomaterial sensors, many inorganic nanomaterial sensors, including gold, carbon dots, quantum dots, and graphene nanoparticles, have been utilized for wastewater monitoring.^{39,40} Although biosensors may cross-react with similar molecules that interfere with their accuracy and stability and require cautious handling, the development of various material-based biosensors is promising for environmental management.

E. Plasmonic biosensors

Plasmonic biosensors have become an important class because of their small size, rapid recognition capability, ease of implementation, and high sensitivity and specificity. Surface plasmonic sensors are important analytical detection tools widely applied in environmental monitoring.

SERS has been extensively used in biosensing because of its high specificity and sensitivity. Srivastava *et al.*⁴¹ developed a SERS biosensor to detect the endocrine-disrupting compound vitellogenin (Vg) in an aquatic environment. To enhance the SERS signal, the biosensor was fabricated by immobilizing anti-Vg antibodies onto a nanosculptured silver thin film coated with 4-aminothiophenol. The biosensor detected concentrations as low as 5 pg/ml, and the specificity was confirmed using a similar protein, fetuin. In another study,⁴² a SERS-based biosensor was employed for *E. coli* B detection in water samples.

Recently, surface plasmon resonance (SPR) biosensors have emerged as a promising approach for environmental monitoring owing to their beneficial properties, such as high sensitivity, selectivity, and accuracy. SPR biosensors are based on the refractive

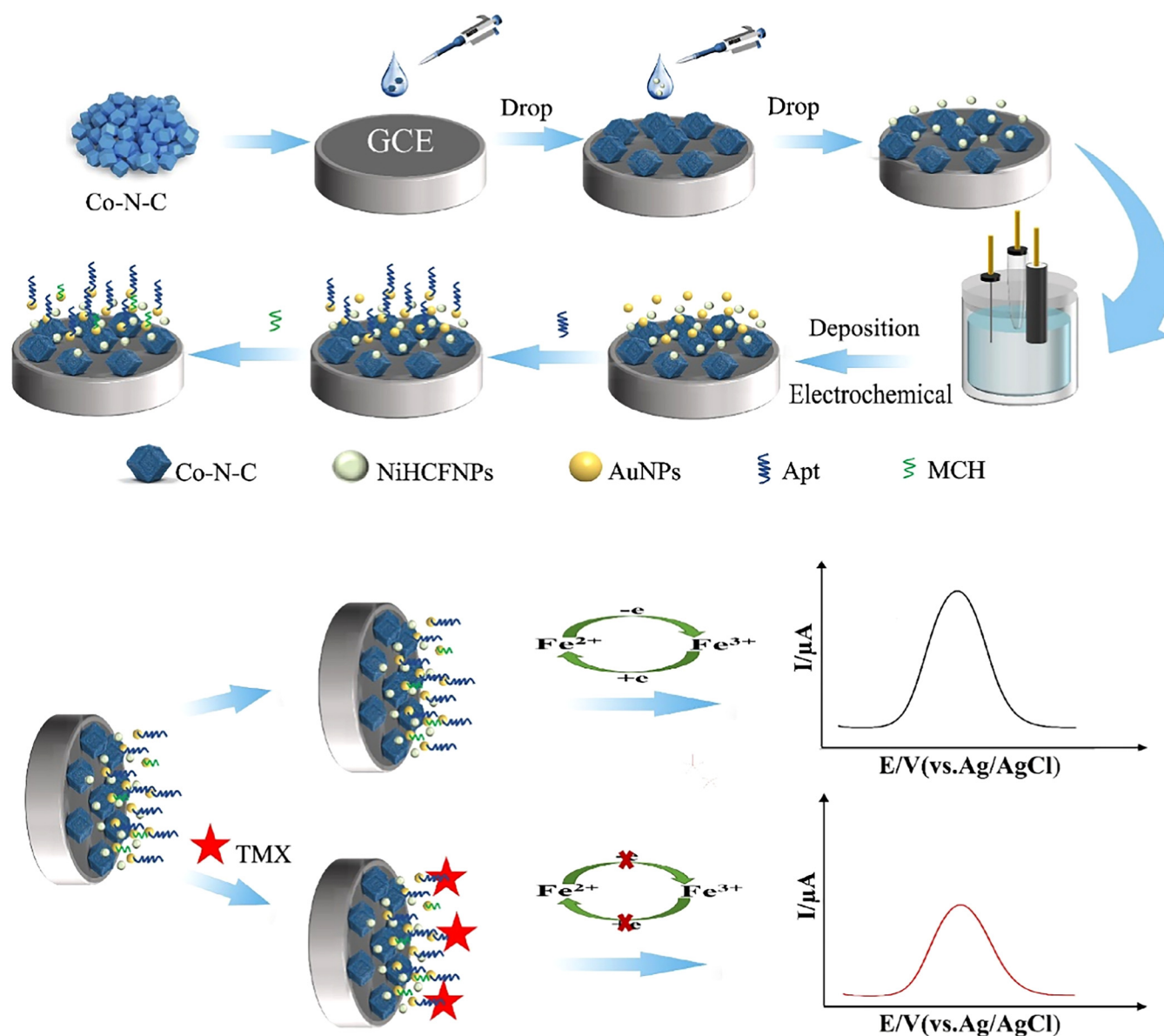


FIG. 3. Schematic illustration showing the fabrication process of the TMX electrochemical aptasensor and the sensing principle of the aptasensor. Reprinted with permission from Shi *et al.*, *Bioelectrochemistry* **149**, 108317 (2023). Copyright (2023) Elsevier.²⁰

index profile of light. When polarized incident light interacts with a metal surface, some energy from the incident light is lost, resulting in a decrease in the intensity of the reflected light. This phenomenon is known as surface plasmon. The SPR signal is highly sensitive to changes near the metal surface. Thus, any change in the refractive index of the metal surface resulting from interactions between biomolecules can generate different SPR signal profiles.

There are two types of plasmonic biosensors: (1) localized surface plasmon resonance (LSPR) biosensors, where surface

plasmons occur in metallic nanoparticles, and (2) SPR biosensors, where surface plasmons occur in a metallic film.^{43,44} Ning *et al.*⁴⁵ used an aptamer for biorecognition coupled with a J-shaped optical fiber probe to specifically detect *Helicobacter pylori* via an LSPR signal response. This LSPR aptasensor can detect *Helicobacter pylori* with a detection limit as low as 45 CFU/ml. The thickness of the sensing layer is critical in the design of plasmonic biosensors and strongly affects their sensitivity. The sensing region of the plasmonic biosensor is close to the metal nanoparticle surface. A thick

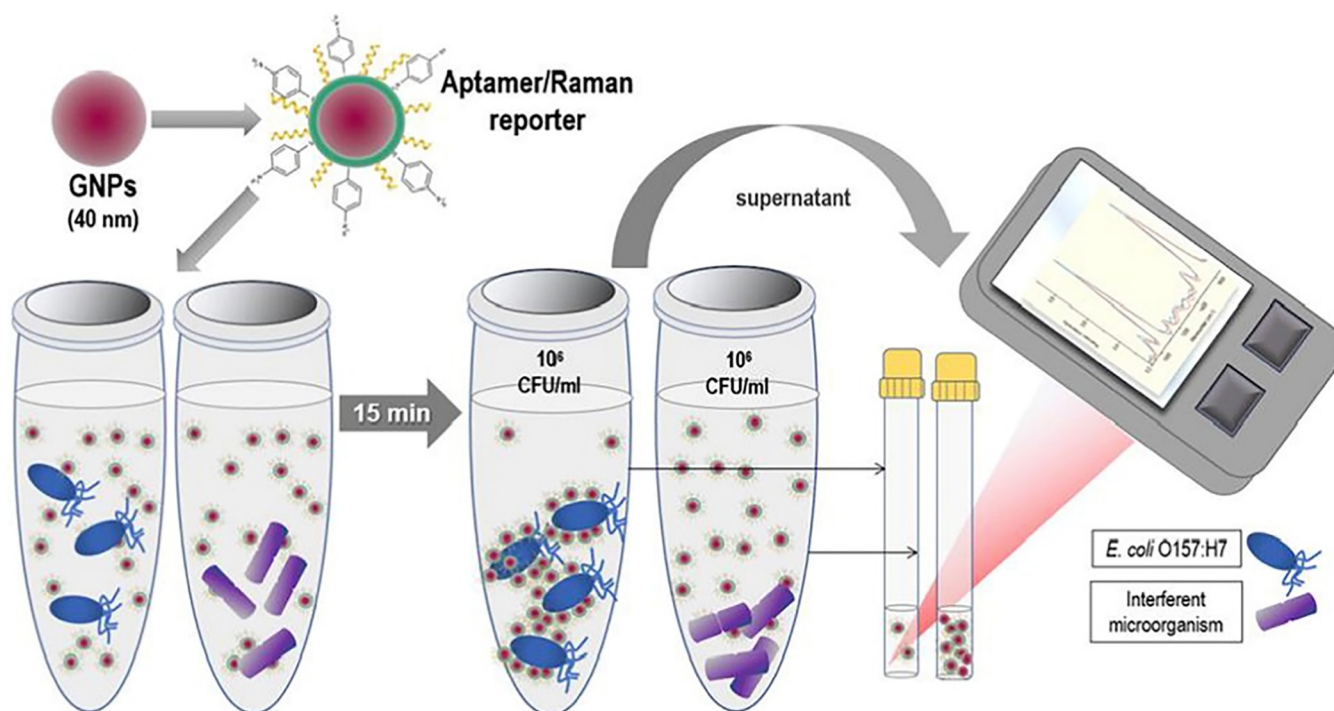


FIG. 4. Schematic illustration showing the detection mechanism proposed for aptamer-based whole-cell detection of *E. coli* O157:H7. Reprinted with permission from Díaz-Amaya *et al.*, *Anal. Chim. Acta* **1081**, 146–156 (2019). Copyright (2019) Elsevier.²⁶

layer of biorecognition elements could lift the sensing event of bacterial attachment outside this sensing region, reducing the sensitivity. Among the listed biorecognition elements, aptamers appear to be more suitable for plasmonic biosensors because they are significantly smaller than enzymes, antibodies, and whole cells.

Khateb *et al.*⁴⁶ obtained a significant increase in sensitivity to bacterial attachment for aptamer recognition compared to antibody recognition, correlating to a thinner aptamer recognition layer (6.2 nm) compared to the antibody layer (20 nm). A novel method for the detection of cyanotoxin from cyanobacteria, which cause algal blooms, was developed based on a graphene-modified SPR aptasensor.⁴⁷ The aptasensor was modified with graphene, which resulted in a change in the aptamer conformation upon binding to analytes, increasing the sensitivity of the sensor for detecting cyanotoxins.

III. MICROFLUIDIC DEVICES IN ENVIRONMENTAL MONITORING

Microfluidics precisely manipulate fluids at the microscale using microchannels and chambers with small dimensions. Many benefits can be achieved using microfluidics for analysis, including a rapid reaction time, high automation, accuracy, sensitivity, specificity, low cost, low reagent and sample consumption, improved process control, and disposability. Microfluidic devices offer many advantages for environmental monitoring owing to the

advancement of miniaturized systems. Previously, silicon and glass were the most commonly used materials for microfluidic fabrication. Currently, more materials are employed to fabricate microfluidic devices, including thermoplastics, polydimethylsiloxane (PDMS), paper, and thread.^{48,49}

Thermoplastics, such as poly(methyl methacrylate) (PMMA), polycarbonate, and polystyrene, have been widely employed to fabricate microfluidic devices owing to their beneficial properties. Thermoplastics exhibit low intrinsic fluorescence, visible transmittance, biocompatibility, and beneficial mechanical properties. In addition, the manufacturing process for thermoplastic microfluidic devices is low-cost and well-developed.⁵⁰

Polydimethylsiloxane (PDMS) is a popular material used for microfluidic fabrication. PDMS is a silicone-based elastomer with several desirable properties. PDMS offers quick and easy fabrication, such as structural replication and bonding processes. Another advantage of PDMS is its transparency, which maximizes the optical access to the microchannel and chamber systems for real-time monitoring. Additionally, PDMS exhibits excellent biocompatibility and permeability.⁵¹

Recently, paper has gained considerable attention for microfluidic fabrication. Paper is a highly promising candidate for the fabrication of microfluidic devices owing to its numerous advantages. Specifically, paper is biocompatible and suitable for the analysis of cells, proteins, or nucleic acids. Paper provides an excellent

matrix for capturing and isolating targets. In addition, the generally bright color of paper makes it a suitable matrix for colorimetric readouts. Moreover, paper-based microfluidic devices can be easily fabricated at a low cost.⁵²

IV. APPLICATIONS OF PORTABLE DEVICES IN ENVIRONMENTAL MONITORING

This section describes the most recent advances in portable devices for environmental monitoring applications, such as microfluidics and biosensors, to detect metal ions, pathogenic bacteria, and other pollutants.

A. Metal ions

Among the various types of environmental pollutants, heavy metal ions are one of the major pollutants owing to their effects on human health, such as kidney failure, skin allergies, and the nervous system.^{53–55} Therefore, many types of analytical biosensors have been developed to detect heavy metals, such as paper, PDMS, thermoplastics, and 3D printed devices.^{56,57} Paper-based microdevices

have been extensively used for heavy-metal detection because of their low cost, simple fabrication, and easy readout.^{58–60}

For example, Wang *et al.*⁶¹ introduced a rotary multipositioned cloth/paper hybrid microfluidic device for the simultaneous detection of Hg^{2+} and Pb^{2+} ions using quantum dots as fluorescence reporters. Figure 5(a) illustrates the overall view of all the layers of the novel rotary multipositioned cloth/paper hybrid microfluidic analytical device for monitoring environmental pollutants. Figure 5(b) illustrates the assembly and detection procedures of the device. For this purpose, the detection zone was first grafted with quantum dots onto cloth. Subsequently, it was frequently modified with ion-imprinted polymers (IIPs) to detect heavy metals based on the fluorescence quenching effect. With the use of IIP, the specific recognition of two heavy metal ions was confirmed, and the limits of detection were 0.18 and 0.07 $\mu\text{g/l}$ for Hg^{2+} and Pb^{2+} , respectively. In addition, this hybrid cellulose-based microfluidic device provided multi-positioned detection owing to its unique configuration, which was designed for valve rotation.

In another study, Yuan *et al.*⁶² fabricated a paper chip for arsenite [As(III)] detection based on a turn-on fluorescent aptasensor using an aptamer, which could detect as low as 0.96 nM.⁶² Gu

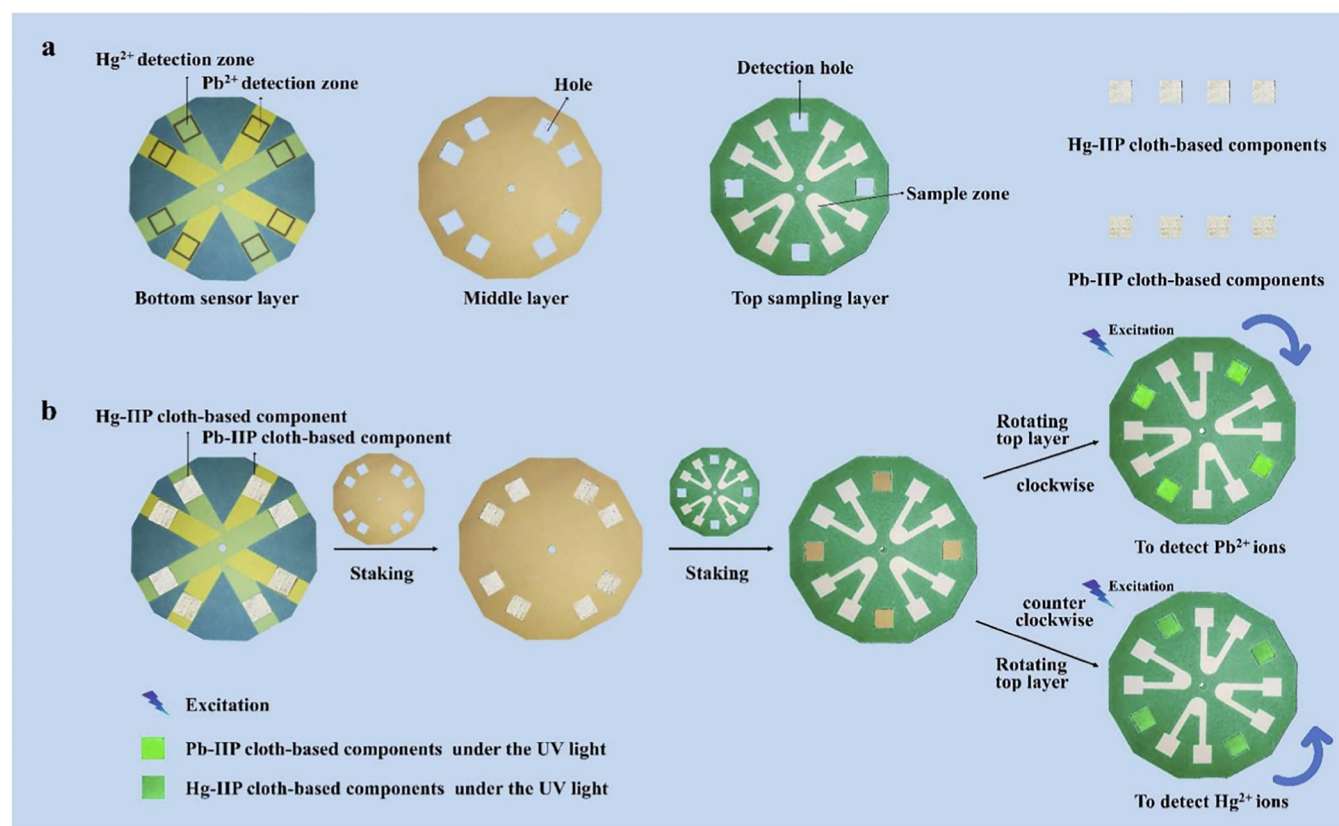


FIG. 5. A schematic illustration of a novel rotary multi-positioned cloth/paper hybrid microfluidic analytical device (μCPAD) for the determination of heavy metal ions. (a) Top view of all layers, (b) the assembly process and detection of Hg^{2+} and Pb^{2+} ions by rotating the top layer counterclockwise or clockwise. Reprinted with permission from Wang *et al.*, J. Hazard. Mater. **428**, 128165 (2022). Copyright (2022) Elsevier.⁶¹

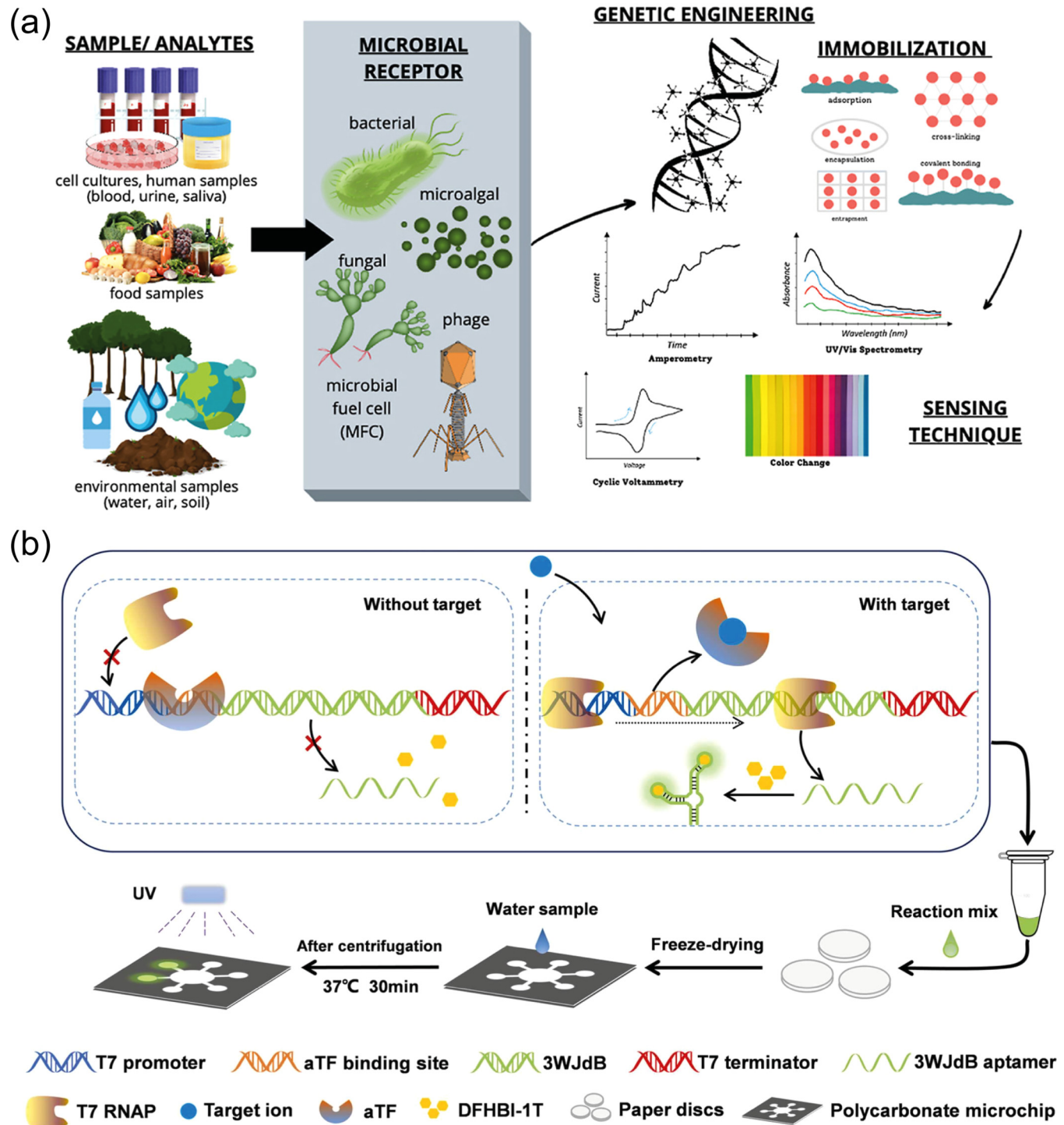


FIG. 6. (a) A schematic illustration showing microbial biosensors for various applications, such as environmental monitoring. Reprinted with permission from Ma *et al.*, *Chemosphere* **306**, 135515 (2022). Copyright (2022) Elsevier.⁶⁵ (b) A schematic illustration of a cell-free paper-based biosensor based on allosteric transcription factors (aTFs) for detecting heavy metal ions. Reprinted with permission from Zhang *et al.*, *J. Hazard. Mater.* **438**, 129499 (2022). Copyright (2022) Elsevier.⁶⁶

*et al.*⁶³ reported a real-time colorimetric biosensor for detecting Hg^{2+} using a low-cost microspectrometer coupled with a smart-phone. Using gold nanoparticles as a probe, the sensor successfully detected Hg^{2+} in natural mineral, pure, tap, and river water samples with high sensitivity ($\text{LOD} = 1.2 \text{ nM}$). This portable device has significant potential for applications in low-cost rapid biological colorimetric detection.

As an alternative to classical biosensors [including atomic absorption spectroscopy (AAS), emission spectroscopy, and mass spectroscopy], microbe-based biosensors have been extensively used for detecting heavy metals in soil and wastewater because of their enhanced sensitivity and specificity [Fig. 6(a)].^{64,65} For example, Wang *et al.*⁶⁷ proposed a highly sensitive electrochemical biosensor for detecting various heavy metals (Cd^{2+} , Ni^{2+} , Pb^{2+} , and Cu^{2+}) in groundwater based on a *Geobacter*-dominated biofilm. With the use of electroactive biofilm on working electrodes, the biosensor was proven to be restorable and reusable, and it achieved a high sensitivity of $61.7 \mu\text{A} \mu\text{M}^{-1} \text{cm}^{-2}$ for Pb^{2+} detection. Moreover, the introduced biosensor has high potential for the on-site monitoring of low-concentration heavy metal ion-related toxicity samples with long-term usage.

Bandeliuk *et al.*⁶⁸ developed a new bacterial biosensor for targeting pollutants (antibiotics, heavy metals, and herbicides) using a portable fiber-optic system. The advances in field toxicological testing were facilitated by combining Raman spectroscopy and bioassays within 35 min. Zhang *et al.*⁶⁶ developed a cell-free paper-based biosensor for the on-site detection of Hg^{2+} and Pb^{2+} in water based on allosteric transcription factors (aTFs) with a BIAcore assay [Fig. 6(b)].⁶⁶ aTFs can recognize and bind to specific DNA sequences. In the presence of target ions, aTFs can disassociate from DNA owing to their specific affinity for metal ions, and fluorescent RNA is transcribed as a signal. The LOD of the biosensor was 0.5 nM for Hg^{2+} and 0.1 nM for Pb^{2+} . The paper-based biosensor not only simultaneously detected Hg^{2+} and Pb^{2+} in water but can also be used to detect other heavy metals, making it a promising biosensor platform for the simultaneous detection of heavy metals in environmental monitoring.

In conclusion, the introduced biosensor platforms require further optimization to improve their sensitivity, specificity, and cost-effectiveness for mass production and multiplex detection. Therefore, portable devices have great potential for detecting heavy

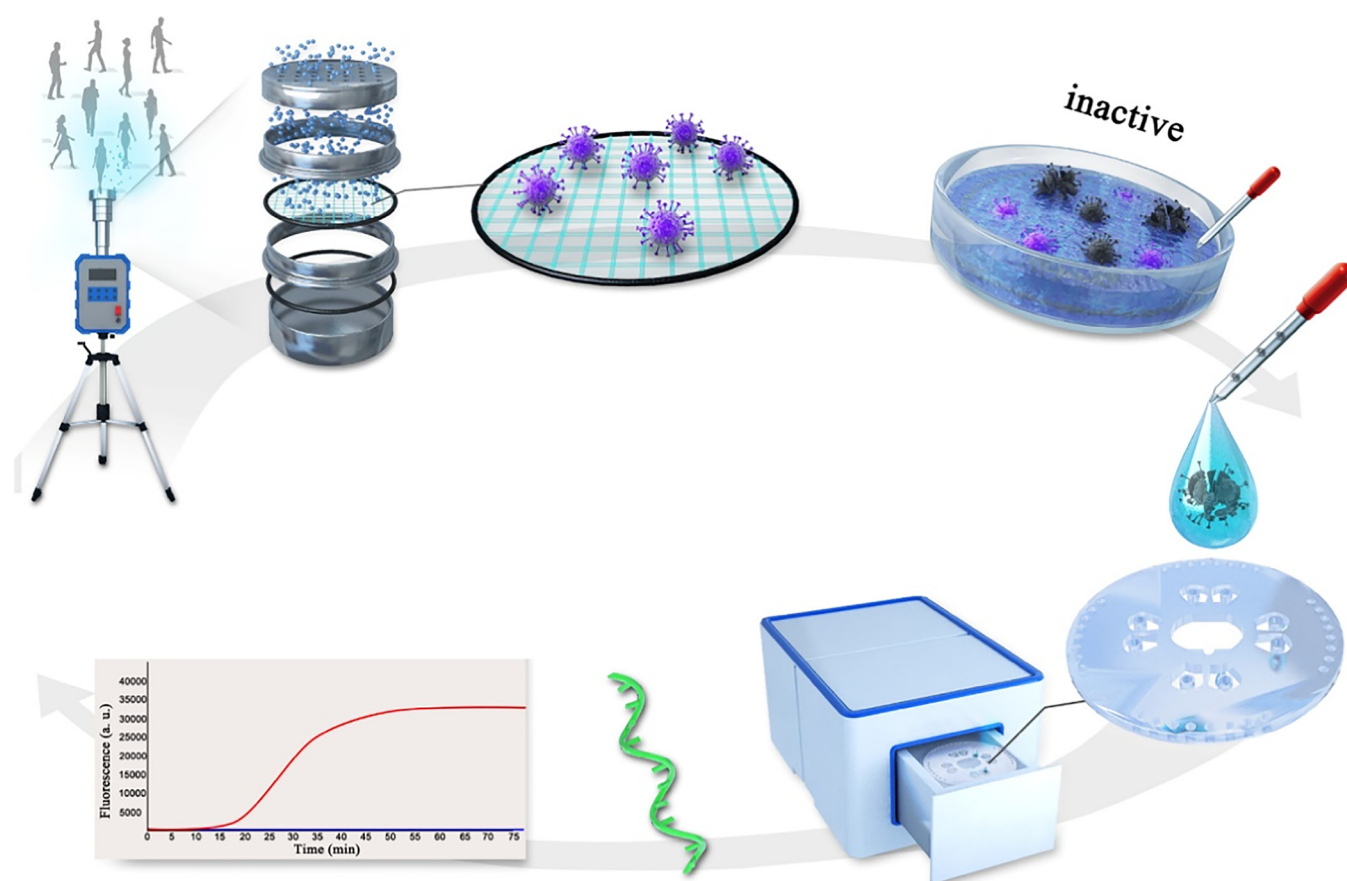


FIG. 7. A schematic illustration showing a rotating microfluidic fluorescence system with integrated sampling and monitoring for the on-site detection of SARS-CoV-2. Reprinted with permission from Xiong *et al.*, *Anal. Chem.* 93(9), 4270–4276 (2021). Copyright (2021) American Chemical Society.⁷⁷

TABLE I. Applications of portable devices for the detection of pathogenic bacteria for environmental monitoring.

Detection method	Type of portable device	Analyses	Type of sample	Time	LOD	Reference
Molecular-based assays	Dual-sample PMMA microfluidic chip	10 waterborne pathogenic bacteria (<i>Vibrio alginolyticus</i> , <i>Shigella flexneri</i> , <i>Listeria monocytogenes</i> , etc.)	Coastal waters	35 min	9.54×10^{-1} pg/reaction	73
Molecular-based assays	Droplet and rotation-controlled “CD driver” device	<i>Enterococcus faecalis</i>	Water	1 h	10^3 CFU/ml	79
Electrochemical immunosensor	Integrated PMMA device	<i>Aeromonas salmonicida</i>	Sea water	5 min	1 CFU/ml	75
Molecular-based assays	Rotating microfluidic fluorescence system	SARS-CoV-2	Air	15 min	10 copies/ μ l	77
Immunoassay	Paper-based analytical device	SARS-CoV-2	Air	<30 min	NA	80
Field-effect-transistor biosensor	Multichannel microfluidic chip	<i>Mycobacterium tuberculosis</i>	Air	2 min	4×10^4 particles/ml	81
Immunoassay and impedance-based biosensor	Glass-PDMS microfluidic chip	<i>Legionella</i> , <i>Salmonella</i> , and <i>Escherichia coli</i> O157:H7	Tap water and wastewater	30–40 min	3 cells/ml	82
Aptamer-based electrochemical assays	PDMS microfluidic biosensor	<i>Cryptosporidium parvum</i>	Tap water	40 min	10 oocysts/ml	83
Surface acoustic waves and Immunoassays	Surface acoustic wave device	<i>Legionella pneumophila</i> , and <i>Escherichia coli</i>	Water	NA	2×10^6 CFU/ml	84

metal ions in real samples under variable environmental conditions in environmental monitoring.

B. Pathogenic bacteria

Various approaches are used in portable devices for the rapid detection of pathogenic bacteria for environmental analysis, offering a high potential for inexpensive, simple, and rapid response field monitoring.^{69–72} For example, Jin *et al.*⁷³ introduced an integrated microfluidic device to simultaneously detect ten waterborne pathogenic bacteria in coastal water samples using dual-sample, real-time, and on-chip fluorogenic loop-mediated isothermal amplification (LAMP) assays.⁷³ The device consisted of 11 wells, which allowed the simultaneous detection of 11 samples based on the LAMP reaction. The primers were pre-stored in each reaction well. The liquid reagent was then introduced into the reaction chamber to perform LAMP assays using centrifugal force. This device could detect as low as 9.54×10^{-1} pg/reaction in 35 min without bacterial enrichment. Although the device can achieve a rapid and high-throughput platform, it requires further optimization for application to real-world samples in aquatic environments.

Alonzo *et al.*⁷⁴ proposed a microfluidic device system to perform a rapid and highly sensitive bacteriophage-based assay for detecting *Escherichia coli* in water samples. With a combination of membrane filtration and selective enrichment using T7-NanoLuc-CBM, the valveless microfluidic device detected as low as 4 CFU/100 ml of drinking water within 5.5h. This system offers a fast, portable, semi-automated, phage-based microfluidic platform for enhanced in-field water quality

monitoring. Messaoud *et al.*⁷⁵ presented a portable label-free ultrasensitive electrochemical immunosensor for *Aeromonas salmonicida* detection in seawater with a LOD as low as 1 CFU/ml.

In another water treatment application, Patinglag *et al.*⁷⁶ used a microfluidic reactor to disinfect bacteria-contaminated water by employing the non-thermal plasma-based inactivation of antibiotic-resistant *Pseudomonas aeruginosa* and *Escherichia coli*. The combination of a glass microfluidic plasma device and dual-phase liquid–gas flow successfully inactivated bacteria 5 s after the residence time in the plasma region. Moreover, this system not only is used for the antimicrobial decontamination of water but can also be used for large volumes of water disinfection systems in point-of-need applications by combining multiple devices.

In addition to water quality monitoring, portable devices have been widely used to detect airborne pathogens in air quality monitoring, particularly during the COVID-19 pandemic. Xiong *et al.*⁷⁷ fabricated a rotating microfluidic fluorescence system for the on-site sample collection and detection of SARS-CoV-2 as shown in Fig. 7. This device could perform enrichment, extraction, and LAMP reaction on a seamless platform, and 115 clinical samples were used for detection in practical applications. The LOD was approximately 10 copies/ μ l with 100% specificity in 75 min. Similarly, Jiang *et al.*⁷⁸ introduced a microfluidic system, including a bacterial capture and enrichment device and a LAMP-based device for *Staphylococcus aureus* detection, with a LOD of approximately 24 cells/reaction.⁷⁸

In summary, these portable devices successfully detected bacteria and airborne pathogens with high specificity and sensitivity,

and the total analysis time was much shorter than that of the traditional methods. However, these devices cannot be used to test real-world samples in practical applications. Therefore, further optimization and development of portable devices with advancements in onsite environmental monitoring are required. Table I summarizes the applications of portable sensing devices for environmental monitoring.

C. Other applications

Antibiotic residues in the environment have become a topic of interest because of their negative effects on human health and

the possible associated bacterial antibiotic resistance. Therefore, portable devices, such as optical sensors and electrochemical biosensors, have been developed for the rapid detection of antibiotics [Fig. 8(a)].^{85,86} For example, Mathai *et al.*⁸⁷ fabricated a handheld device to detect enrofloxacin (ENR) and ciprofloxacin antibiotic residues in wastewater and environment samples [Fig. 8(b)]. Using an antibody-coated optical fiber, the system could detect concentrations as low as 1 ppb in lake water and wastewater. Moreover, the portable sensors showed stability over 4 weeks at 4 °C with high selectivity. Therefore, this handheld device is useful for heavy-metal detection as a field-deployable sensor that can be easily stored and

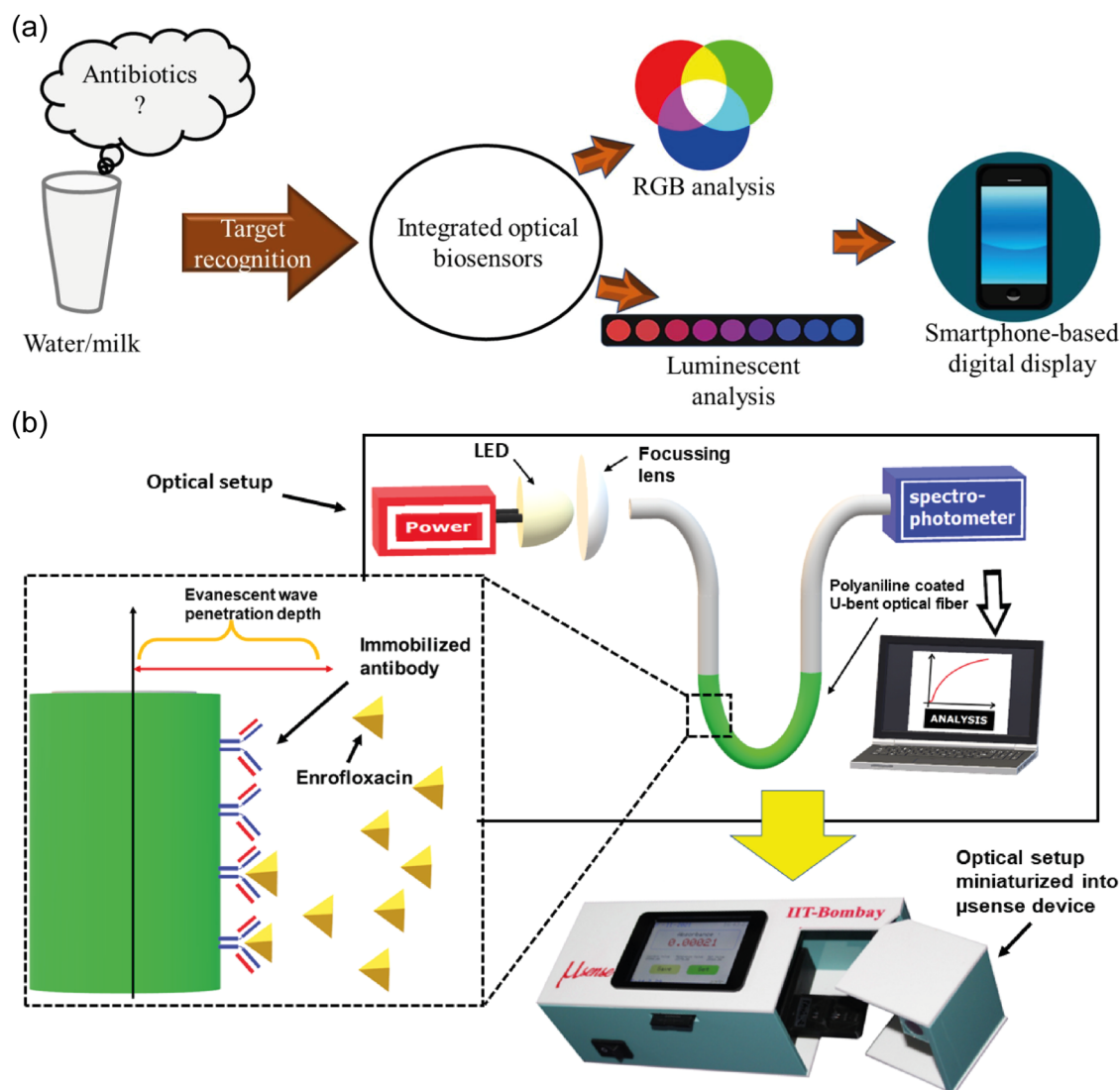


FIG. 8. (a) A schematic illustration of the detection of antibiotics using optical biosensors. Reprinted with permission from Nehra *et al.*, Mater. Lett. **308**, 131235 (2022). Copyright (2022) Elsevier.⁸⁵ (b) A schematic illustration of an overall experimental setup for controlling a handheld portable optical sensor for the specific detection of enrofloxacin (ENR). Reprinted with permission from Mathai *et al.* Biosens. Bioelectron. **237**, 115478 (2023). Copyright (2023) Elsevier.⁸⁷

transported to remote areas. Chen *et al.*⁸⁸ developed a portable biosensor for onsite kanamycin (KAN) detection in real water samples using a glucometer and CRISPR-Cas12a, with a detection limit of 1 pM.⁸⁸ These portable devices are simple to operate, cheap, and enable the on-site detection of antibiotic residues in resource-limited settings. However, these devices fail to perform simultaneous assays with multiple antibiotics, which requires further improvement.

Pesticide residues are important pollutants that cause environmental, agricultural, and aquatic pollution. Therefore, portable biosensors have been fabricated for the onsite detection of pesticide residues.^{89–91} For example, Maanaki *et al.*⁹² developed an integrated smartphone/resistive biosensor as a field-deployable tool for monitoring organophosphate (OP) pesticides in food and environmental water with an LOD of approximately 0.304 ppt in 15 min. In particular, for the first time, a polyaniline nanofiber/AChE/carbon nanotube (AChE/PANiNF/CNT)-based nanosensor was used for the on-site rapid monitoring of OP pesticides in real water samples with high sensitivity, low cost, and portability. However, this platform requires further development to enhance the long-term stability and reduce the interference effects of AChE for broad applications for in-field real-world sample analysis. Wu *et al.*⁹³ proposed a novel smartphone-coupled three-layered paper-based microfluidic chip for pesticide detection. Based on enzyme inhibition and chromatic reactions, the device was successfully used for the detection of profenofos and methomyl pesticides, with LODs of approximately 55 and 34 nM, respectively. This system not only is highly cost-effective, but also shows high potential for the mass production of paper-based microdevices.

Polycyclic aromatic hydrocarbon (PAH)-organic compounds are usually highly toxic, mutagenic, and/or carcinogenic to microorganisms or humans and are considered toxic environmental pollutants.⁹⁴ Various portable devices have been developed for the rapid detection of PAH. For example, Zheng *et al.*⁹⁵ introduced an integrated microfluidic system for the rapid enrichment and detection of airborne PAHs with an LOD of 3.3 ng/m³ within 25 min.⁹⁵ With the use of an enrichment cube, the device achieved a high capture efficiency, which allowed the transfer of PAHs from the enrichment cube to the detection device without extraction steps using a crushing motion. The device demonstrated a high potential for air pollution monitoring owing to its low cost, high sensitivity, rapidity, and high throughput. Li *et al.*⁹⁶ developed a monoclonal antibodies-based biosensor for PAH detection in aqueous environmental samples, with an LOD of approximately 0.2 µg/l within 10 min. Generic antibody-based biosensors offer a low-cost and rapid technique for detecting PAHs in aqueous samples. Babolghani and Mohammadi-Manesh⁹⁷ conducted a simulation and experimental study of a field-effect-transistor (FET) biosensor to detect PAHs using a DNA/Cu₂O-GS nanostructure.

Overall, portable microfluidic devices or biosensors have been introduced as alternatives to expensive, time-consuming, and laboratory-based testing systems for the detection of environmental pollutants. These promising characteristics make the portable device a powerful tool for environmental monitoring. However, these platforms still have limitations in monitoring pollutants from a variety of sources or different ecosystems. Further improvements are required to realize highly selective and sensitive detection of analytes for various applications.

V. CONCLUSIONS AND PERSPECTIVES

The demand for efficient methods to control environmental pollution has attracted significant attention to the development of portable sensing devices. In this review, the advancements in microfluidic devices and biosensors for environmental pollutant monitoring were discussed. Environmental control using microfluidics and biosensors is a promising advancement owing to their fast analysis time, low cost, ease of use, and accuracy. The devices are suitable for on-site testing, particularly in low-resource areas. However, several limitations must be overcome with further improvement of the biosensors:

- Biosensors provide an excellent tool for measuring analytes by generating signals proportional to the concentration of the analyte. However, biosensors cannot be used for sample preparation, which is an essential step in monitoring pollutants, because they do not have the required components. By contrast, microfluidic devices contain microchannels and chambers that enable fluid flow and biochemical reactions. This property renders microfluidic devices highly suitable for sample preparation. Thus, biosensors should be integrated with microfluidic devices to perform all essential steps in pollutant monitoring.
- Most biosensors for pesticide detection use enzymes as recognition factors, which provide fast, selective, and accurate detection. However, their real-world applications are still limited because of the thermal- and pH-sensitive properties of the enzymes, which make long-term storage more difficult.
- Although immune-based devices provide high specificity and rapid performance, difficulties in immobilization onto sensor substrates and poor regeneration make the development of devices more difficult.
- The main limitation in the application of devices to real samples is the lack of research on the variation of samples because most environmental monitoring devices focus on water, which is much simpler in comparison with complicated environmental samples. Consequently, only a small number of environmental monitoring devices have been successfully commercialized.
- Further optimization is required to improve the specificity, sensitivity, and reproducibility of the mass production and detection of real samples. Further research should be conducted to study the performance and shelf-life of these devices using different environmental samples.
- Finally, the portability of biosensors for monitoring in field environments is limited for many reasons, including sample preparation methods, device integration, fluid-handling techniques, biological reagent storage conditions, and the requirement for power and external equipment.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Thi Ngoc Diep Trinh: Conceptualization (equal); Methodology (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Nguyen Khoi Song Tran:** Methodology (equal); Writing – review & editing (equal). **Hanh An Nguyen:** Methodology (equal); Writing – review & editing (equal). **Nguyen Minh Chon:** Visualization (equal); Writing – original draft (equal). **Kieu The Loan Trinh:** Conceptualization (equal); Methodology (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Nae Yoon Lee:** Funding acquisition (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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