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Article

# Smartphone-assisted Electrochemical Sensors for Environmental Monitoring

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**Abstract:** The rise of industrialization and urbanization has exacerbated environmental pollution, raising public concern about environmental quality. Real-time pollutant detection and rapid responses to environmental changes are crucial for safeguarding both the environment and human health. Traditional chemical analysis methods, though accurate and sensitive, are expensive, complex, and require specialized equipment and personnel. In contrast, smartphone-assisted electrochemical sensors could offer a novel, rapid, sensitive, and cost-effective solution for environmental monitoring. In this review, the working principle of electrochemical sensors was first introduced, including how their sensing elements and conversion systems work together to generate an electrical signal proportional to the concentration of the target substance. Next, the role of smartphones in this system was discussed. The challenges faced in designing smartphone assisted electrochemical sensor systems were also discussed in detail. In terms of applications, this article reviews the latest progress of smartphone assisted electrochemical sensors in detecting heavy metal ions, mycotoxins, bacteria, the veterinary drug and pesticide residues, and other compounds, and discusses their potential in environmental monitoring and public health. Despite hurdles in technology integration and data processing, smartphone-assisted electrochemical sensors are poised to become increasingly vital in environmental monitoring as technology progresses and is gradually becoming a powerful tool for cross industry monitoring and analysis.

**Keywords:** electrochemical sensors; smartphone configurations; on-site detection; environmental pollutants

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# 0 Introduction

As industrialization and urbanization accelerate, environmental pollution is worsening, heightening public concern over environmental quality. Timely monitoring of pollutants and swift responses to environmental changes are crucial for protecting both the environment and human health[1]. For decades, advanced techniques like gas and liquid chromatography, capillary electrophoresis, and mass spectrometry have been the primary methods for detecting chemicals in biomedical, environmental, and food samples[2]. Although these techniques offer high specificity and low detection limits, they come with certain drawbacks. These sophisticated instruments are typically expensive, require specialized laboratories and trained personnel, and involve time-consuming processes such as sample preparation, analysis, and data interpretation[3]. The demand for accurate detection methods has spurred the development of sensor technology as a versatile tool adaptable to everyday life[4]. Consequently, it is vital to explore and innovate simpler, more convenient detectors, with the smartphone emerging as a promising alternative.

Converting sensor data into manageable electronic signals is a complex task, making direct smartphone connections to sensor systems challenging[5,6]. However, smartphone-based electrochemical sensors offer a solution[7,8]. With smartphones becoming essential tools for billions, their integration of high-definition cameras, powerful processors, and various sensors can be leveraged for chemical experiments[9]. These devices, combined with electrochemical sensors, enable the rapid and sensitive detection of specific pollutants in environmental samples[10]. This advancement allows environmental monitoring to move beyond the laboratory, providing portable and cost-effective solutions[11]. The increasing sophistication of smartphones and the flexibility of their operating systems and applications create vast opportunities for environmental monitoring technologies. By downloading specialized applications, users can conduct real-time monitoring of environmental parameters and perform data analysis on the go[12]. In this review, the design of smartphone-assisted electrochemical sensor systems, various applications of the sensors for the detection of heavy metal ions, mycotoxins, bacteria, the veterinary drug and pesticide residues and other compounds are discussed. The applications and advantages of various sensors are further summarized in Table 1.

# 1 Design of smartphone-assisted electrochemical sensor systems

## *1.1 Mechanism of electrochemical sensors*

Electrochemical sensors are a specialized type of sensor used in modern analytical chemistry. These sensors utilize a specific sensing element that reacts with the target substance, generating a signal which is converted into an electrical signal proportional to the concentration of the target. This process allows for qualitative or quantitative analysis and detection of the target substance (Fig.1a)[13]. Electrochemical sensors consist of two main components: a fixed sensing element (recognition system) and a transducer (conversion system). The sensing element is formed by fixing materials with specific recognition functions on a surface. This recognition system serves two primary roles: it reacts specifically with the target substance and converts the reaction parameters into a signal that can be processed by the conduction system. The generated signal is then received by the transducer, which also has dual functions. Firstly, it converts the received signals into measurable electrical or electrochemical signals. Secondly, it processes these signals through secondary amplification and electronic systems. Finally, the processed signals are recorded and displayed by an instrument. The secondary amplified electrical signal is directly proportional to the concentration of the target substance, enabling accurate analysis and detection based on their linear relationship. This relationship ensures that the measured electrical signal can be used to deduce the concentration of the target substance effectively[11,14].

## *1.2 The role of smartphone*

Smartphones have emerged as key tools in portable detection, becoming a research focal point in recent years.

Table 1 Application and detection performance of sensors

| Sensors | Pollutants | Detection performance |
|---|---|---|
| Smartphone-controlled NFC Potentiostat Sensor[15] | As(III), Cr(VI), Hg(II), Cd(II), and Pb(II) | There is no significant difference compared to the ICP-OES method and it can be widely used for the detection of heavy metals with high accuracy and reliability. |
| Screen-printed electrode-based portable electrochemical sensors[16] | Hg$^{2+}$ and Cu$^{2+}$ ion | Highly sensitive, comparable to commercial precision instruments. |
| Based on a portable U-disk electrochemical workstation in combination with a screen-printed electrode (SPE)[17] | Zearalenone (ZEN) | A wide linear range of 1 pg mL$^{-1}$–10.0 ng mL$^{-1}$ with a detection limit of 0.389 pg mL$^{-1}$ (at 3δ) was obtained. Demonstrates superior sensitivity, selectivity and reproducibility. |
| A mobile phone platform for biomolecular analytical detection[18] | Plasmodium falciparum histidine-rich protein 2 (PfHRP2) | In contrast to commercial ELISAs that require 2-3 hours, this mobile phone-based assay is completed in 15 min. |
| Listeria biosensor based on platinum interdigitated microelectrodes (Pt-IME)[19] | Listeria | Sensitivity of 3.37 ± 0.21 kΩ log-CFU$^{-1}$ mL, and the LOD was 48 ± 12 CFU mL$^{-1}$ with a linear range of 10$^{2}$ to10$^{4}$ CFU mL$^{-1}$. Able to meet the needs of rapid and sensitive and on-site detection. |
| Microfluidic EIS bacteria pre-concentrator and sensor based on a smartphone[20] | Coli cells | Low-cost, portable, enables pre-concentration of bacterial solutions and achieves detection limits as low as 10 cells per milliliter with a dynamic range from 10 cells/ml to 1,000 cells/ml. |
| Wearable Flexible and Stretchable Glove Biosensor[21] | Organophosphate (OP) | With high sensitivity, good selectivity, stability and applicability, it is ideally suited for rapid on-site detection of organophosphorus compounds. |
| Smartphone-based cyclic voltammetry system[22] | Glucose | Low-cost, easy-to-operate, linear, sensitive and specific response to glucose with a detection limit of 0.026 mM. |
| An intelligent sensor of ascorbic acid based on graphene microelectrode[23] | Ascorbic acid | The results showed that the concentration of AA had a good linear relationship in the range of 0.01-0.5 mg/mL at pH 1. High precision, selectivity and good reproducibility. |

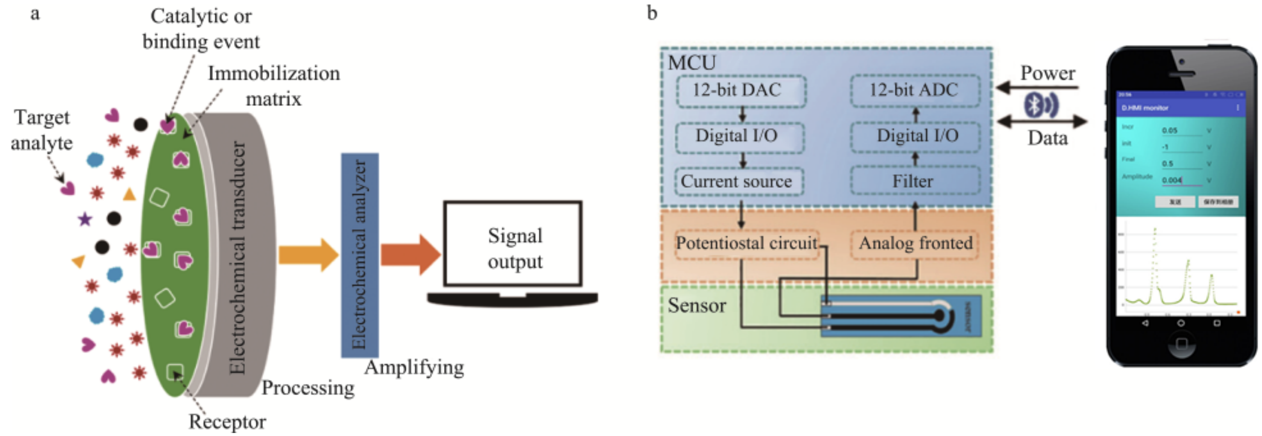


Fig.1 (a) The configuration and working principle of an electrochemical sensor[13]. (b) Smartphone measuring current[26].

Detection technologies using smartphones are primarily categorized into electrochemical and optical methods[24]. Smartphone-based electrochemical detection involves using the smartphone as the central unit, paired with portable sensors like printed paper electrodes and microfluidic chips. These sensors, along with various electrochemical techniques, form a compact measurement circuit for sensing purposes[25]. Typically, smartphones manage the detection process via Bluetooth, Wi-Fi, audio ports, USB, and other connections, enabling real-time control and rapid completion of the electrochemical determination, with immediate display of results (Fig.1b)[13,26].

### *1.3 Difficulties in designed systems*

Although researchers have done a lot of work in smartphone detection devices and methods, they still face huge challenges before smartphone-based detection technology is truly used for environmental monitoring, disease diagnosis, and other work. It requires various fields such as micro/nano processing, electronic information technology, and medicine to work together to overcome these challenges[18]. From the perspective of the portability and precision requirements of biochemical testing, the difficulties encountered in the design of smartphone assisted electrochemical sensor systems mainly lie in the following three aspects:

i) With the increasing demand for portability and detection accuracy, effectively integrating advanced nanotechnology, biometric recognition, and microfluidic technologies into miniaturized sensors while maintaining or enhancing their performance has become a significant challenge in technological development. This not only requires achieving the integration and innovation of technologies at the hardware level but also ensuring that these integrated devices meet the growing performance standards.

ii) The computational power of smartphones has provided new possibilities for complex data processing and intelligent analysis. To make full use of the computing power of smartphones and combine it with artificial intelligence algorithms for big data processing and intelligent analysis, it is necessary to develop more efficient and accurate data processing algorithms. These algorithms must be designed scientifically and also ensure effective operation on resource-constrained mobile devices.

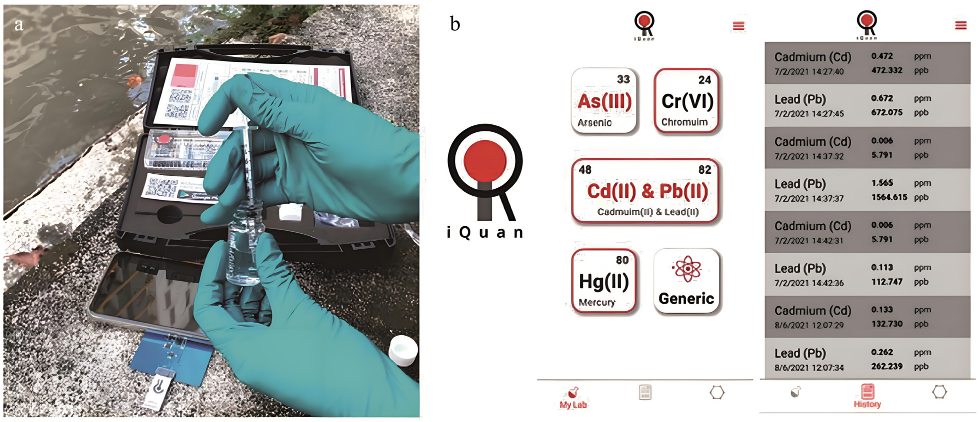
iii) User experience and data security are also important aspects that cannot be ignored in design. Enhancing the usability and intuitiveness of user interactions, while ensuring the security and privacy protection of data, is a critical aspect of user experience design. As the sensitivity of health data increases, how to design user interfaces and back-end systems that are easy to operate for the user and secure the data is a key issue to be addressed in the future.

## 2 Common chemicals using smartphone-assisted electrochemical sensor systems

### *2.1 Determination of heavy metal ions*

Heavy metal pollution has emerged as a critical issue undermining global environmental quality. Toxic metals such as arsenic (As), chromium (Cr), mercury (Hg), cadmium (Cd), and lead (Pb) pose severe health risks, threatening both human health and ecosystems[27]. These heavy metals can inflict damage on the skin, nervous system, urinary system, and skeletal structure[28]. Additionally, certain heavy metals are classified as carcinogens, potentially leading to serious cancer-related illnesses. Detection of these contaminants typically relies on methods like Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), and Atomic Absorption Spectrometry (AAS)[29]. Despite their accuracy, these technologies are constrained by the need for specialized operators, costly and cumbersome equipment, and lengthy analytical processes. Consequently, their use in field analysis is limited, particularly in scenarios necessitating frequent monitoring.

Pungjunun et al. developed a compact electrochemical sensor capable of detecting five heavy metals (As (III), Cr (VI), Hg (II), Cd (II), Pb (II)) via a smartphone-controlled NFC potentiostat[15]. The system features NFC (near-field communications)-enabled circuit boards and enhanced electrodes, managed through wireless communication and data conversion displays, permitting smartphone operation (Fig.2). The designed



Cadmium (Cd) 7/2/2021 14:27:40 0.472 ppm 472.332 ppb
Lead (Pb) 7/2/2021 14:27:45 0.672 ppm 672.075 ppb
Cadmium (Cd) 7/2/2021 14:37:32 0.006 ppm 5.791 ppb
Lead (Pb) 7/2/2021 14:37:37 1.565 ppm 1564.615 ppb
Cadmium (Cd) 7/2/2021 14:42:31 0.006 ppm 5.791 ppb
Lead (Pb) 7/2/2021 14:42:36 0.113 ppm 112.747 ppb
Cadmium (Cd) 8/6/2021 12:07:29 0.133 ppm 132.730 ppb
Lead (Pb) 8/6/2021 12:07:34 0.262 ppm 262.239 ppb

Fig.2 (a) Photograph of a ready-to-use toolbox developed for on-field analysis.
(b) The example of the detection data displayed on the smartphone application[15].

sensor's activity showed no significant deviation from the traditional ICP-OES method at a 95% confidence level, with recovery rates ranging from 80% to 111%. This cost-effective, NFC-integrated device stands out for its portability, ease of use, and remarkable performance. It exemplifies the integration of smartphones with NFC technology to manage electrochemical analytical equipment, paving the way for new smartphone-based detection systems. The screen-printed graphene electrodes (SPGE) used in the sensor serve as a reference point for developing other portable electrochemical sensors. Additionally, the device's sensitivity and selectivity can be fine-tuned for various heavy metals, ensuring optimal detection. It stands out in sensitively identifying heavy metals, and the electrodes exhibit consistent performance across batches, making them suitable for large-scale industrial production. This study introduces a portable sensor ideal for fast, on-site detection, with significant practical applications in environmental monitoring and food safety testing.

Bao et al. have developed a portable electrochemical mini workstation for the quantitative detection of $Hg^{2+}$and $Cu^{2+}$ ion concentrations in tap water[16]. The electrodes are prepared using a cost-effective screen printing process and integrated with a compact electrochemical analysis device, a rapid signal acquisition system, and a transmission module that allows data analysis via a smartphone. In addition, the detection results of tap water components are highly consistent with laboratory test results, which proves that the performance of the equipment can be comparable to high-precision instruments on the market. This study is notable for its innovative design and functionality, especially in incorporating OLED and Bluetooth technology. It offers a portable sensor ideal for quick on-site detection, which is highly valuable for real-time monitoring of water quality pollution. Compared to traditional high-precision analysis methods, this portable sensor is significantly more cost-effective and easier to promote and apply. The use of Bluetooth for wireless data transmission offers a technical solution for other remote monitoring systems and serves as a reference for the detection of other heavy metal ions.

## 2.2 Determination of mycotoxins

Fungi produce a large number of different bioactive substances during their metabolism, which are called mycotoxins due to their toxicity to humans and animals[30]. Common mycotoxins include aflatoxins, ochratoxins, and zearalenone, among others. Toxins are often distributed in agricultural products, such as corn and wheat, which can cause the loss of nutrients in crops, leading to crop spoilage and deterioration. They also have a certain degree of inhibitory effect on the synthesis of important substances in human and animal bodies, such as proteins. Human or animal ingestion of food contaminated with mycotoxins can induce mycotoxin poisoning, such as vomiting, bleeding, dermatitis, central nervous system and organ damage, and even cause tumors or death[31]. In recent years, the pollution of crops by fungal toxins has become increasingly severe. According to investigations, the contamination of crops by fungal toxins has become the biggest obstacle for China's exports of agricultural products to the European Union. In light of current needs, devising innovative and precise methods to detect toxins and ensure food safety and quality has become an inevitable trend. Traditional techniques for high-precision and high-sensitivity detection of fungal toxins, such as thin-layer chromatography (TLC), GC-MS, and HPLC-MS, though effective, have notable limitations[32]. These include lengthy detection times, multiple operational steps, and potential human error.

Chen et al. developed a portable U-disk electrochemical workstation coupled with a screen-printed electrode (SPE)-based aptamer sensor for the quantitative detection of zearalenone (ZEN)[17]. This sensor utilizes an aptamer immobilized on a covalent organic framework (COF) made of Au nanoparticles and Ce-TpBpy, coated on a glassy carbon electrode. The specific binding of ZEN to its aptamer inhibits electron transfer, thereby reducing the hydrogen peroxide reduction catalytic current, which is measured via the timed current method (i-t). This reduction in catalytic current allows for the quantitative detection of ZEN toxin. The sensor demonstrates a broad linear detection range from 1 pg/mL to 10.0 ng/mL with a detection limit of 0.389 pg/mL (at 3δ, , Fig.3). Recovery

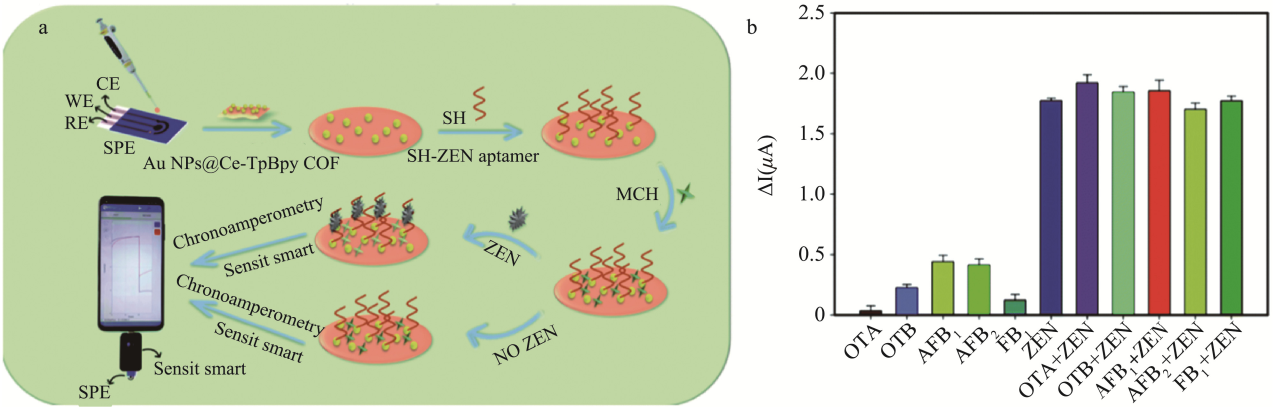


Fig.3 (a) The preparation process of ZEN aptamer sensors.
(b) The interference of five common food toxins on aptamer sensors[17].

rates in corn flour samples ranged from 93.0% to 104.7%, exhibiting excellent sensitivity, selectivity, and reproducibility. This system combines Au nanoparticles with COFs as novel nano-enzymes to enhance electrochemical sensor performance, providing a new direction for developing advanced detection materials. By anchoring the aptamer on SPE and employing Au NPs@Ce-TpBpy for signal amplification, a method for designing highly sensitive sensors is proposed. This approach could inspire future research on integrating aptamers with other recognition elements. The study presents an effective means for the quantitative analysis of ZEN in food, potentially serving as a reference for developing assays for other food contaminants.

Lillehoj et al. developed a mobile phone platform for biomolecular analysis and detection[18]. The system includes embedded circuits for signal processing and data analysis, alongside disposable microfluidic chips for fluid handling and biosensing. Capillary flow facilitates sample loading, processing, and pumping, enhancing both portability and simplicity. A graphical, step-by-step guide on the smartphone screen fosters the operator throughout the testing process. Upon completion of each measurement, results are instantly displayed on the screen for immediate evaluation, and the data are automatically saved for future analysis and transmission. In Fig.4, the device's effectiveness was validated by detecting Plasmodium falciparum histidine-rich protein 2 (PfHRP2), a crucial malaria biomarker. The identification of PfHRP2 is realized through a highly specific protein capture strategy coupled with a sensitive enzymatic signal enhancement process. Unlike commercial ELISAs that take 2-3 h for analysis, this smartphone-based assay delivers results within 15 min. The system serves as a low-cost, high-efficiency diagnostic tool particularly useful in regions with limited medical resources. It exemplifies the integration of microfluidic technology, electrochemical detection, and smartphone capabilities, opening up new avenues for the development of portable medical devices and environmental sensors in the future.

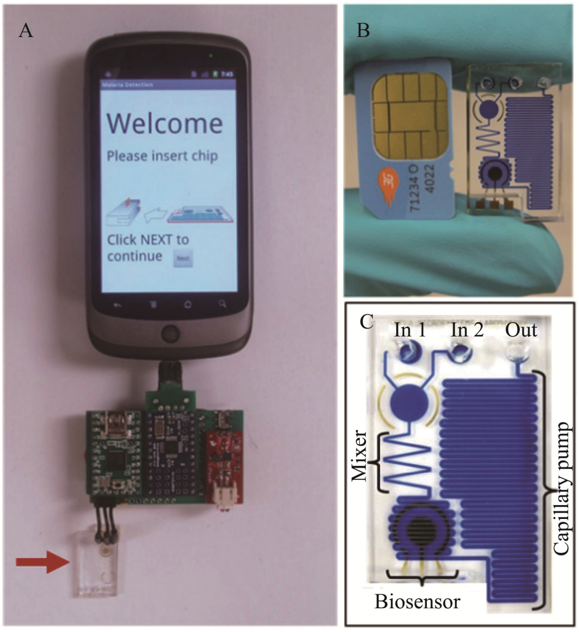


Fig.4 (A) A photo of the assembled device, with arrows indicating the microfluidic chip. (B) Compare photos of chips and mobile SIM cards. (C) Magnified image of a chip with labelled components. The channels are filled with dye for improved visualization of the fluidic network[18].

## *2.3 Determination of bacteria*

Bacteria are found everywhere in the environment and within the human body, exposing us to numerous bacterial species daily. Luckily, most of these bacteria are harmless, and some even establish beneficial relationships with their hosts[33]. Nevertheless, pathogenic strains exist and pose significant threats to public health. Foodborne illnesses, resulting from eating contaminated food, are among the primary food safety concerns. The World Health Organization (WHO) reports 600 million cases of foodborne diseases annually, leading to 420,000 deaths. In the United States, foodborne illnesses are estimated to cause over $50 billion in losses each year[34]. Rapid identification of pathogens in transmission pathways is crucial for inhibiting their spread and preventing disease outbreaks[35]. Several methods are available to detect bacteria in various samples, including plate counting, polymerase chain reaction, and loop-mediated isothermal amplification. However, traditional bacterial testing methods tend to be time-consuming and labor-intensive, taking hours to days to yield results. They are also costly and require skilled personnel. Given the rising demand for efficient testing, traditional methods increasingly fall short of practical needs[36]. Electrochemical sensors, on the other hand, have gained prominence in bacterial detection due to their low detection limits, ease of operation, high sensitivity, and specificity. These sensors offer a promising alternative, addressing the limitations of conventional testing methods in meeting the needs of contemporary food safety and public health monitoring.

Sidhu et al. introduced an innovative aptasensor for detecting Listeria using platinum interdigitated microelectrodes (Pt-IME)[19]. This innovative sensor is integrated into a particle/sediment trap for real-time water quality analysis in hydroponic lettuce systems. Equipped with a potentiostat linked to a smartphone, it facilitates rapid on-site water quality evaluation. Detailed electrochemical characterization was carried out, which included calibration with or without DNA and Listeria monocytogenes in various flow conditions (Fig.5). Under flow conditions (100 mL samples), the aptasensor exhibited a sensitivity of 3.37 ± 0.21 kΩ log-CFU$^{-1}$ mL and a limit of detection (LOD) of 48 ± 12 CFU mL$^{-1}$, with a linear range of 102 to 104 CFU mL$^{-1}$. The sensor's performance improved significantly in stagnant conditions in buffer solution, vegetable broth, and hydroponic culture media.

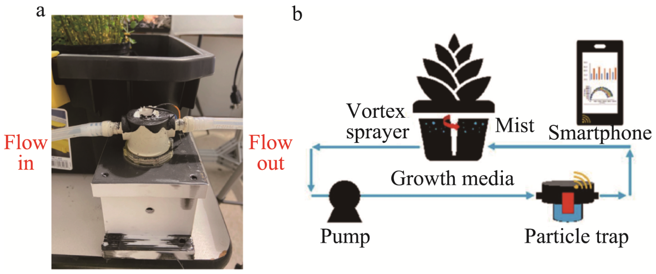


Fig.5 (a) Pt-IME incorporated into particle flow trap for continuous analysis. (b) Schematic diagram of circulation system[19].

This pioneering study is the first to utilize an aptamer sensor for real-time monitoring of microbial water quality in hydroponic lettuce systems, leveraging a smartphone-based acquisition system. The aptamer sensor achieved a 90% recovery rate and could be reused with minimal cleaning steps. This system merges advanced biosensor technology with smartphone capabilities, offering a novel solution for pathogen detection in hydroponic settings. The rapid, on-site detection provided by this system enhances agricultural water quality monitoring, consequently improving food safety and public health. The study offers a comprehensive description of the sensor's design, including electrode construction, biological functionalization, and electrochemical testing, serving as a valuable reference for further sensor development. Additionally, the integration of data science techniques, such as machine learning, introduces new methods for enhancing detection sensitivity and accuracy.

Jiang et al. developed a portable and affordable bacterial pre-concentration microfluidic sensor and impedance sensing system utilizing a smartphone platform[20]. By utilizing electrochemical impedance spectroscopy (EIS), they designed a cost-effective, miniaturized, and sensitive bacterial sensor operable via a smartphone. The system includes several key components:

i) Microfluidic design: Features a chip to pre-concentrate bacteria in samples through specific filtering structures.

ii) Sensor microfabrication: Utilizes interleaved electrodes on a silicon chip to detect impedance changes due to bacteria presence.

iii) Impedance conversion network analyzer chip: Works with a microcontroller to measure and analyze impedance.

iv) Wireless system: Incorporates a Bluetooth module and microcontroller for data transmission to a smartphone.

v) Smartphone application: An Android app developed for controlling sensor electronics, recording, and displaying test results.

As shown in Fig.6, this study successfully created a low-cost, portable wireless bacterial sensor capable of pre-concentrating bacterial solutions, detecting as few as 10 cells per milliliter, with a dynamic range from 10 to 1,000 cells/ml. This work highlights the integration of advanced microfluidic and impedance sensing technologies into portable devices, particularly utilizing smartphones as platforms. It offers a valuable reference for future development of similar portable detection tools, thoroughly examining EIS technology's application in bacterial detection. The study provides an efficient method for detecting microorganisms, potentially inspiring further research on EIS-based biosensors.

## *2.4 Determination of veterinary drug and pesticide residues*

Pesticides and veterinary drugs play a pivotal role in boosting food production and enhancing animal reproduction and aquaculture[37]. They are extensively used in modern agriculture to manage weeds, pests, and regulate plant growth, while veterinary medicines are employed to prevent and treat diseases and promote growth in animals[38]. These substances help avert significant losses in agriculture and animal husbandry, allowing these sectors to meet the escalating demands of the global population[39]. Nevertheless, overuse or misuse of pesticides and veterinary drugs can lead to residues in food and the environment, posing health risks through the food chain. Consequently, effective residue detection methods have been established to monitor food safety and protect public health. At present, traditional methods for detecting food contaminants often involve technologies like

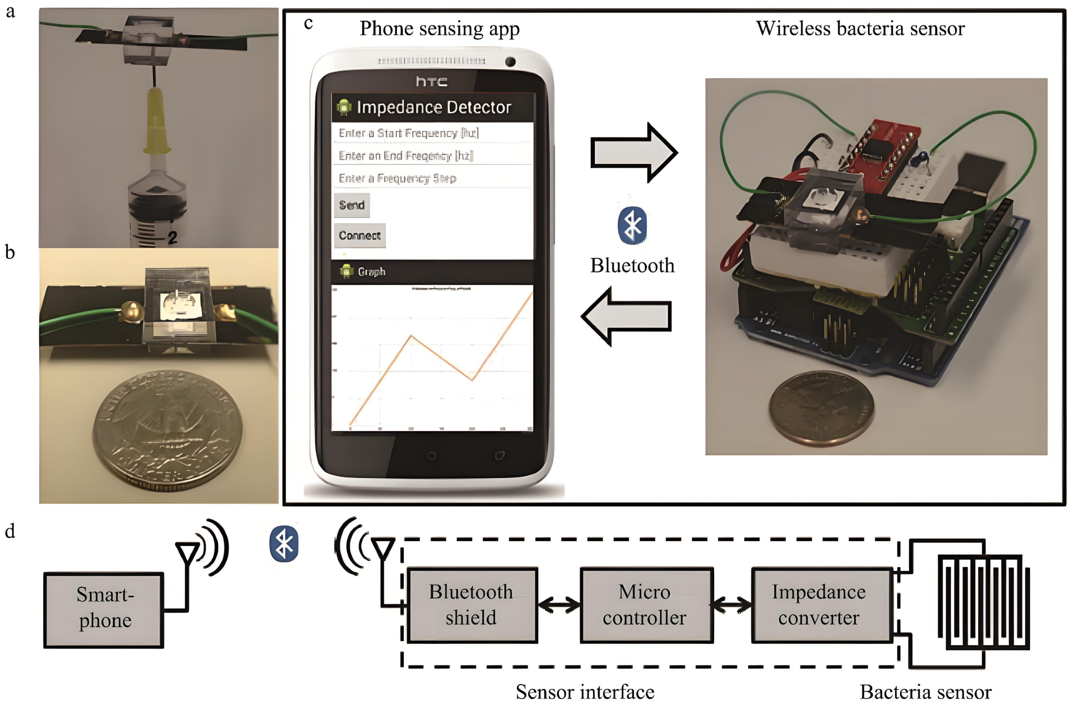


Fig.6 System diagram. (a) Inject the test liquid into the sensor packaging using a syringe. (b) Close up view of the EIS bacterial sensor packaging. (c) Communication scheme between smartphone sensing application and wireless bacterial sensor. (d) Wireless sensing system diagram[20].

HPLC, GC, GC-MS, AAS, capillary electrophoresis, and ELISA. Despite their effectiveness, these methods are time-consuming, costly, and require complex preprocessing, specialized skills, and bulky equipment, limiting their feasibility for rapid on-site food safety testing[40].

However, in a significant breakthrough, Mishra et al. developed a wearable, flexible, and stretchable glove biosensor designed for on-site detection of organophosphorus (OP) chemical threats, including pesticides and nerve agents[21]. This innovative sensor utilizes an organophosphorus hydrolase (Oph) biosensor system, which catalyzes the hydrolysis of OP compounds, producing a detectable electrochemical signal. By employing square-wave voltammetry (SWV) to measure p-nitrophenol-a product of the Oph-catalyzed enzymatic reaction-the sensor sends real-time data to a smartphone for immediate monitoring and analysis. Field tests in Fig.7, have demonstrated the glove biosensor's efficacy in detecting OP chemicals on various surfaces and agricultural products, emphasizing its potential for real-time, on-site chemical threat screening. This advanced device, merging nanotechnology and wearable technology, offers a novel method for promptly identifying organophosphorus nerve agent compounds. It serves multiple applications, including military, forensic, consumer protection, and food safety, setting a precedent for the future development of similar wearable sensors across various domains.

## *2.5 Determination of other compounds*

Ji et al. have developed a smartphone-based CV system incorporating graphene-modified screen printed electrodes (SPE), which are modified with 3-aminophenylboronic acid (APBA) for glucose detection[22]. The system's primary components include smartphones, modified electrodes, and a portable electrochemical detector. The detector features an energy conversion module for stimulus signal application and a low-cost potentiostat module for CV measurements, complete with Bluetooth for data and command transmission. In Fig.8, the system exhibits a linear, sensitive, and specific response to glucose, with a detection limit of 0.026 mM, making it highly relevant for clinical diagnosis and personal health monitoring. This detection method is also applicable to various biological samples such as sweat and urine. Moreover, the system demonstrates excellent selectivity, accurately detecting glucose in serum samples amidst numerous chemical substances. Its low cost, user-friendly operation, and real-time data capability suggest it could significantly impact global health, particularly in resource-limited areas. The potential for electrode detection and modification extends to fields like public health, water monitoring, and food quality, highlighting its broad applicability.

Wang et al. developed an advanced sensor for ascorbic acid (AA) using graphene microelectrodes[23]. These electrodes were created with the laser-induced graphene (LIG) technique. The Palm Sens USB-type electrochemical analyzer, paired with a smartphone, was utilized to measure the electrochemical response of the graphene electrodes to AA through the CV in Fig.9. The experimental findings reveal that under pH 1, AA detection shows a robust linear response within the concentration range of 0.01 to 0.5 mg/mL, indicating its high sensitivity. Furthermore, interference tests with other substances confirmed this method’s good selectivity. The

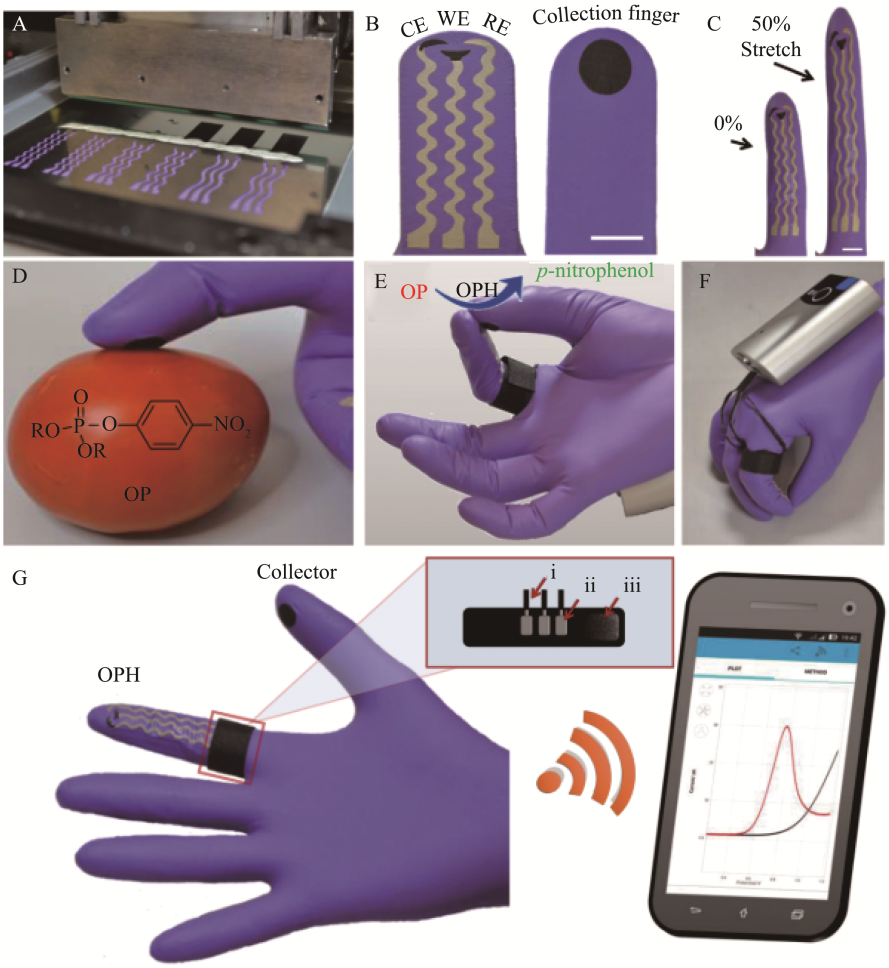


Fig.7 Flexible glove biosensor Schematic[21].

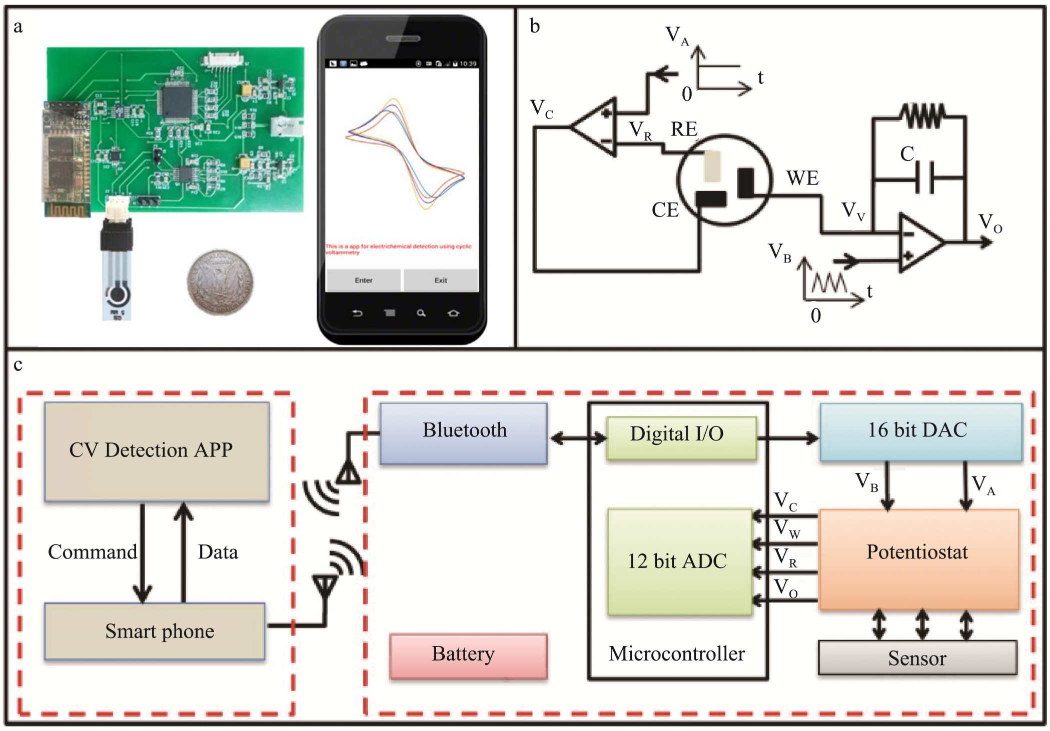


Fig.8 System design and schematic diagram. (a) Image of handheld detector connected to SPE and welcome interface of app on smartphone. (b) The circuit design of the potentiostat based on a resistive feedback transimpedance amplifier. (c) A schematic diagram of the smartphone-based CV system[22].

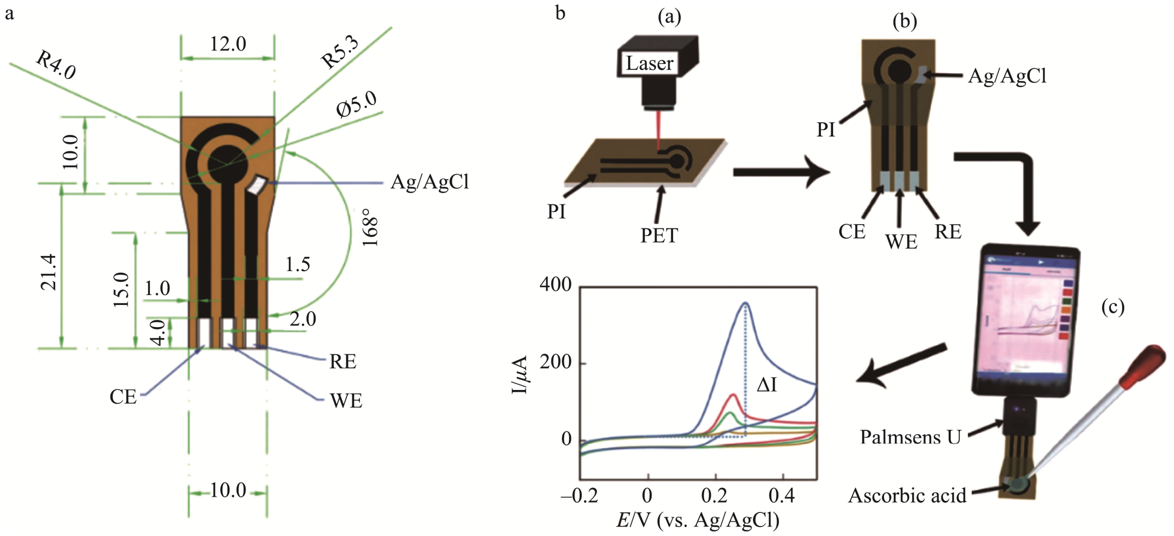


Fig.9 (a) The design diagram of LIG electrode (unit: mm). (b) Preparation of LIG electrodes and smartphone detection process[23].

practicality of this detection technique was confirmed through the analysis of artificial urine and sweat samples, with recovery rates within an acceptable range, suggesting its potential for real-world applications. This research not only introduces a novel approach for AA detection but also implies that the principle can be applied to detect other chemicals. By modifying the electrode surface or optimizing detection conditions, this method can potentially be extended to detect more environmental pollutants.

# 3 Challenges and perspectives

Smartphone-assisted electrochemical sensors hold great promise for environmental monitoring, but several technical challenges must be addressed for their practical adoption. First, the sensitivity and selectivity of these sensors are vital; they must accurately detect low concentrations of pollutants while distinguishing between similar compounds. Additionally, their stability and repeatability are crucial for reliable long-term monitoring, imposing the development of durable materials and technologies resilient to environmental conditions. Simplifying sample preparation is also essential for rapid on-site detection, requiring sensors that can analyze complex samples without extensive pre-processing. Miniaturization and integration are key to making these sensors portable and user-friendly, which is especially important for monitoring in remote or hard-to-reach areas. Reliable data transmission and processing are critical for leveraging the capabilities of smartphones. Ensuring stable and secure wireless communication between sensors and smartphones, along with effective data collection, storage, and analysis, is essential. Cost-effectiveness is another crucial factor for widespread adoption, requiring research into affordable production methods. User-friendliness is paramount for acceptance by non-professional users. This involves developing intuitive interfaces and guidance to make environmental monitoring accessible to the public.

The current progress has significantly improved the sensitivity and selectivity of sensors through the application of nanotechnology and achieved the portability and user-friendly operation interface of sensors through miniaturization technology. In addition, the powerful computing power of smartphones is used to perform complex data processing and intelligent analysis, while the application of cloud platforms and big data technology enables real-time transmission and analysis of data.

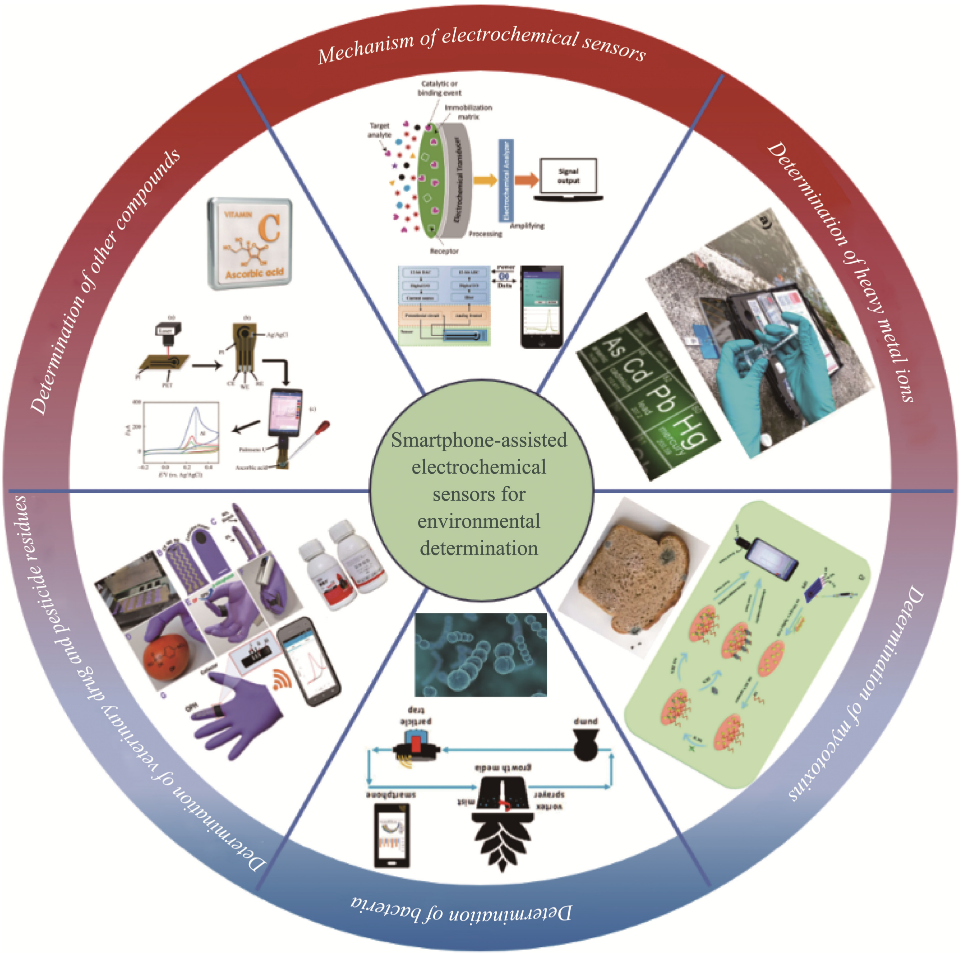
Looking ahead, smartphone-assisted electrochemical sensor technology is expected to make significant progress in multiple aspects. With the continuous emergence of new sensitive materials, such as nanocomposites, biosensors, and conductive polymers, the sensitivity and selectivity of sensors will be significantly enhanced. The application of machine learning and artificial intelligence algorithms will significantly enhance the intelligence level of data processing. Future technological advancements will further optimize the size, energy consumption, and ease of use of sensors, making smartphone-assisted electrochemical detection technology more operable and popularized, suitable for a broader range of user groups and application scenarios. Integration of this technology will not only enhance existing diagnostic tools but may also revolutionize the way we monitor health and the environment. The popularization of smartphones and the development of biosensing technology are leading significant changes in fields such as healthcare, biodiversity monitoring, food safety, and environmental monitoring.

# 4 Conclusions

Smartphone-assisted electrochemical sensors have emerged as a promising innovation in environmental monitoring. This work explores the design principles, diverse applications, challenges, and prospects of this technology. Numerous efforts have demonstrated the effectiveness and convenience of these sensors in detecting heavy metal ions, mycotoxins, bacteria, veterinary drug residues, pesticides, and other chemicals. The review highlights cutting-edge technologies such as electrochemical sensors, portable electrochemical mini-stations, and aptamer sensors, showcasing how they integrate with smartphones for rapid on-site detection.

These sensors exhibit high sensitivity and selectivity in identifying target analytes, meeting stringent analytical requirements for environmental monitoring. Real-time data processing through smartphone applications and user-friendly interfaces enhances data readability and operational convenience, lowering the technical barrier for users. The low manufacturing cost and the ubiquity of smartphones expand the market potential of this technology, particularly in resource-limited regions. Despite challenges in technological integration, data processing, user experience, and data security, advancements in material science, nanotechnology, and data analysis are expected to enhance their role in future environmental monitoring. These sensors are ready to offer robust technical support for environmental protection. In addition to their traditional applications in environmental monitoring, these sensors hold significant potential and exhibit promising prospects in various domains, including agriculture, food safety, healthcare, public health, industrial process control, toxicology, forensic science, and educational research. Particularly, in the realm of healthcare, the advent of wearable technology has positioned these sensors to facilitate personalized health monitoring and preventative medicine.

## Graphical Abstract



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The authors declare that the main data supporting the findings of this study are available within the paper and its Supplementary Information files.

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The authors declare no competing interests.

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