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Voltammetric Sensing in Portable and Point-of-Care Devices: A Review of Recent Trends and Applications

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ABSTRACT

The growing demand for rapid, low-cost, and decentralized analytical technologies has driven the development of portable voltammetric sensors and point-of-care (POC) devices. This review examines recent advancements in miniaturized voltammetric systems, with a particular emphasis on innovations in screen-printed electrodes (SPEs), microfluidic integration, plug-and-play configurations, and smartphone-enabled electrochemical platforms. These technological developments exhibit substantial potential for real-time, on-site analytical applications across various fields, including medical diagnostics, environmental monitoring, food safety, and wearable health technologies. Several studies are highlighted to illustrate the practical implementation of voltammetric sensing, including glucose and uric acid detection, cancer biomarker analysis, heavy metal monitoring, pesticide screening, and nitrite and formaldehyde detection in food. The review also discusses major challenges such as signal noise, sensor stability, energy constraints, and the need for user-friendly interfaces. Finally, it outlines future research directions, focusing on the incorporation of artificial intelligence (AI), the Internet of Things (IoT), and low-power electronics to enable fully autonomous and smart diagnostic systems. These developments position voltammetric sensing as a vital tool in the future of accessible, real-time, and personalized analytical technologies.

Keyword: Electrochemical sensing, Portable devices, Point-of-care testing (POCT), Voltammetric sensors

I. INTRODUCTION

In the modern era, the demand for fast, easy-to-use, and cost-effective analytical methods is increasing, especially outside central laboratories. This is particularly important in various fields such as medical diagnostics, industrial quality control, and environmental monitoring (Dincer et al., 2019). Portable sensors and point-of-care (POC) devices have emerged as innovative solutions that facilitate on-site analysis, eliminating the necessity for sophisticated laboratory instrumentation (Rasheed et al., 2024).

Portable sensors are small and lightweight devices that can be easily transported and used in various locations, while POC devices serve as diagnostic instruments intended for deployment in close proximity to patient care environments, delivering swift results to support prompt and informed clinical decision-making (Lin et al., 2025; Zhang et al., 2024). Traditional lab-based methods, such as HPLC and spectroscopy, often require expensive instrumentation, trained personnel, and time-consuming procedures, their utility is limited in resource-constrained environments and for immediate monitoring purposes (He et al., 2023). In contrast, portable sensors and POC devices enable decentralized testing with several advantages such as on-site analysis: enabling applications like bedside diagnostics and environmental monitoring (Li et al., 2021; Zhang et al., 2024); Cost efficiency: achieved through disposable components and minimal reagent consumption (Ahmed et al., 2015); Rapid turnaround times: producing results within minutes rather than hours (Arshavsky-Graham & Segal, 2020).

Voltammetry is an electrochemical method that analyzes current variations in response to an applied potential (Allen J. Bard, Larry R. Faulkner, 2022) employs a three-electrode system immersed in an electroactive solution. The working electrode's (WE) potential is linearly swept across a defined potential window relative to a stable reference electrode (RE), while the counter electrode (CE) completes the circuit. This controlled potential sweep enables the observation and analysis of analyte redox reactions occurring at different potentials (Kalita et al., 2023). Its high sensitivity and selectivity (dependent on electrode modification), versatility in analyzing various analytes, and relatively simple instrumentation requirements have positioned voltammetry as a promising solution for portable and point-of-care (POC) applications (Mahari et al., 2020; Yakoh et al., 2021). Furthermore, recent advancements in microelectrode fabrication and miniaturization techniques have facilitated the development of portable and low-power voltammetric systems (Vishnu et al., 2020). The principle relies on redox reactions at an electrode surface, where analyte concentration is proportional to the measured current.

Voltammetry offers diverse techniques for electrochemical analysis. Cyclic voltammetry (CV) elucidates reaction mechanisms using a triangular potential sweep. Pulsed methods like normal pulse voltammetry (NPV), differential pulse voltammetry (DPV), and square wave voltammetry (SWV) provide high sensitivity, enabling trace-level detection and rapid, high-resolution analysis. These techniques collectively enable comprehensive electrochemical studies and precise analyte quantification (Ramaley & Krause, 1969; Chen & Shah, 2013).

This review article highlights the latest advancements in the development and application of miniaturized voltammetric sensors integrated into portable and point-of-care (POC) devices. It highlights key technological advancements such as the use of screen-printed electrodes, microfluidic systems, plug-and-play configurations, and integration with microcontrollers and smartphones. The article examines their application across multiple fields, such as medical diagnostics, environmental surveillance, food safety assurance, and wearable health technologies. Special attention is given to the challenges associated with sensor miniaturization, signal stability, energy efficiency, and user interface design. In addition, future research directions are outlined, focusing on multi-analyte detection, integration of artificial intelligence (AI) and the Internet of Things (IoT), and the advancement of robust, low-cost, and high-performance voltammetric platforms for real-world applications.

II. PRINCIPLES OF VOLTAMMETRY

Voltammetry is an electroanalytical technique that studies the relationship between the electric current flowing through an electrochemical cell and the potential applied to the working electrode. In voltammetry, the potential of the working electrode is controlled and systematically changed, and the resulting current in response to this potential change is measured. The information obtained from a voltammogram (a plot of current versus potential) can be used to identify electroactive species, determine their concentrations, and study electrochemical reaction mechanisms. This technique utilizes a three-electrode configuration, comprising a working electrode, a reference electrode, and a counter electrode, along with a supporting electrolyte to ensure good conductivity (Fig. 1). The fundamental principle is the occurrence of oxidation or reduction reactions at the surface of the working electrode when the appropriate potential is applied, generating a current flow proportional to the concentration of the electroactive species reaching the electrode surface. Voltammetry is highly sensitive and selective, making it suitable for the detection of a wide range of compounds, from heavy metals to biomolecules (Douglas A. Skoog, Donald M. West, F. James Holler, 2013; Allen J. Bard, Larry R. Faulkner, 2022).

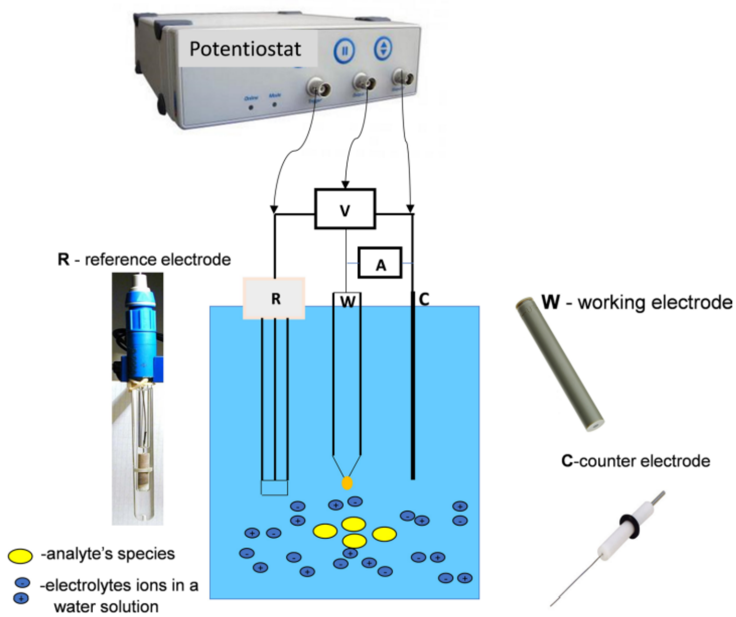

Figure 1. Schematic representation in voltammetric experiments (Gulaboski & Mirceski, 2024)

In research and development, diverse voltammetry methods are widely employed, each offering unique capabilities for electrochemical analysis. Among these, Cyclic Voltammetry (CV) stands as a fundamental and extensively utilized electroanalytical technique across numerous fields of chemistry. While its primary application is not in quantitative determination, CV proves invaluable for investigating redox mechanisms, elucidating reaction intermediates, and assessing the stability of reaction products. Beyond CV, pulse voltammetry methods have been developed to enhance both speed and sensitivity. This category encompasses three principal techniques. Normal Pulse Voltammetry (NPV) operates by measuring the current at the culmination of a series of increasing potential pulses, allowing sufficient time for the non-faradaic charging current to decay before measurement. Differential Pulse Voltammetry (DPV), conversely, quantifies the current difference immediately before and after small, fixed-amplitude pulses that are superimposed upon a slowly changing base potential. Lastly, Square-Wave Voltammetry (SWV) distinguishes itself by employing a symmetrical square-wave pulse, calculating the net current from the differential between forward and reverse current measurements. SWV is particularly esteemed for its high sensitivity, excellent rejection of background currents, and remarkable speed, rendering it an ideal choice for studying electrode kinetics, conducting trace detection, and integrating with High-Performance Liquid Chromatography (HPLC) systems (Kounaves, 1997).

To adapt voltammetry into portable sensors, several modifications are necessary, especially in terms of miniaturization and power efficiency. The basic principles of voltammetry can be implemented in small and low-power devices through several key adaptations. Miniaturization of electronic components, microelectrochemical cell design, and the use of printed electrodes are the main strategies. The potentiostat, the device that controls the potential and measures the current, can be made in small sizes with low power consumption thanks to advances in microelectronics and embedded systems technology (Krorakai et al., 2021). The microelectrochemical cell design reduces the volume of solution required, which indirectly reduces power needs and the overall size of the device. The use of printed electrodes eliminates the need for complex and expensive conventional electrode fabrication, allowing for the mass production of compact and uniform sensors. With this approach, voltammetry systems that typically require large laboratory instruments can be transformed into efficient handheld devices (Shi et al., 2008; Said et al., 2017; Silva et al., 2021).

III. DEVELOPMENT OF PORTABLE VOLTAMMETRIC SENSORS

Several recent studies have specifically emphasized the development of portable voltammetric sensors through the use of printed electrodes, particularly screen-printed electrodes (SPEs). SPEs are widely favored due to their low production cost, scalability for mass fabrication, and versatile compatibility with various substrates. One of the primary advantages of SPEs is their inherent miniaturization, which facilitates seamless integration into portable and field-deployable devices. In addition, their application for in situ measurements significantly minimizes or even eliminates potential errors, reduces analysis time, and lowers the costs associated with sample collection, transport, and storage (Hayat & Marty, 2014).

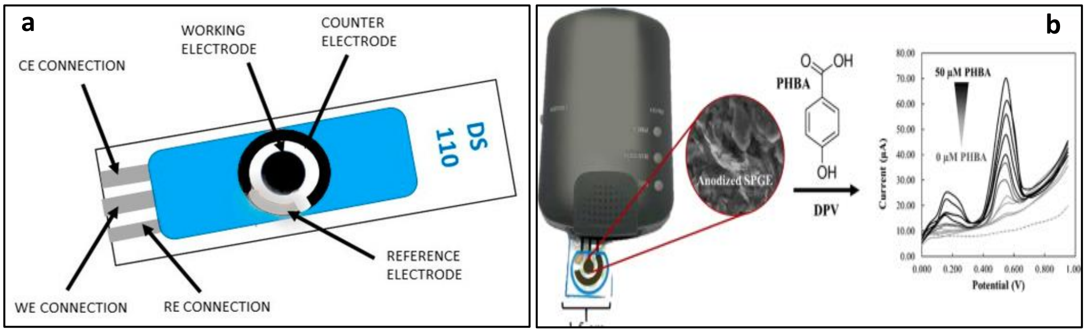

Figure 2. (a) screen-printed electrodes (Mincu et al., 2020); (b) Schematic representation of a portable voltammetric sensing system for p-hydroxybenzoic acid (PHBA) detection using an anodized screen-printed graphite electrode (SPGE) (Charoenkitamorn et al., 2022).

Seguro et al., (2022) reported the development of a Molecularly Imprinted Polymer-modified Screen-Printed Carbon Electrode (MIP/SPCE) sensor using Differential Pulse Voltammetry (DPV) in combination to detect trazodone (TZD), used as an antidepressant. The sensor showed a linear response between 5 and 80 µM, a detection limit (LOD) of 1,6 µM, good selectivity, rapid analysis within approximately 30 minutes, and it was successfully analyze spiked tap water and human serum samples. Furthermore, Charoenkitamorn et al., (2022) developed a screen-printed graphene electrode (SPGE), anodized in phosphate buffer solution, for measuring para-hydroxybenzoic acid (PHBA) in cosmetic products. This sensor achieved a significantly enhanced sensitivity, with an LOD of 0,073 µmol/L, and proved to be highly effective for real sample analysis. Although it faced limitations related to the potential window, its suitability for mass production and on-site analysis using a portable potentiostat marks it as a highly promising device. Furthermore, Cardoso Gomes-Junior et al., (2024) developed a disposable screen-printed carbon electrode (SPCE), modified with multi-walled carbon nanotubes (MWCNTs) and platinum nanoparticles (PtNPs), designed for the sensitive measurement of uric acid (UA) in biological samples, and used a miniaturized potentiostat operated by a smartphone. The combination of nanomaterials and Nafion™ formed a stable electroactive layer. The sensor exhibited a markedly enhanced current response for UA due to the synergistic interaction of PtNPs and MWCNTs, achieving an impressive LOD of 4,9 × 10^{-7} mol/L, along with excellent repeatability and strong anti-interference performance.

In addition to the use of screen-printed electrodes, another key innovation in the development of portable sensors is the integration of microfluidic systems. Microfluidics is a technique that enables the precise manipulation of fluids within extremely small channels, primarily designed to extract samples from larger environments. This method plays a vital role in the miniaturization of analytical devices and promotes the integration of lab-on-a-chip systems into other technologies, thus allowing for the efficient analysis of complex samples (Felemban et al., 2022). One notable advancement in this field is the development of microfabricated electrochemical cells, which offer a sensitive and compact alternative to conventional systems. These devices typically consist of Polydimethylsiloxane (PDMS) microchannels integrated with gold microelectrodes. The dual-patterned electrode design enhances signal detection and minimizes electrical interference. Demonstrating performance on par with traditional setups, such microcells have been successfully applied for the rapid detection of analytes such as ferrocyanide, cysteine, and guanosine, including DNA characterization—highlighting their potential as disposable platforms for quick and sensitive analysis (Chand et al., 2013).

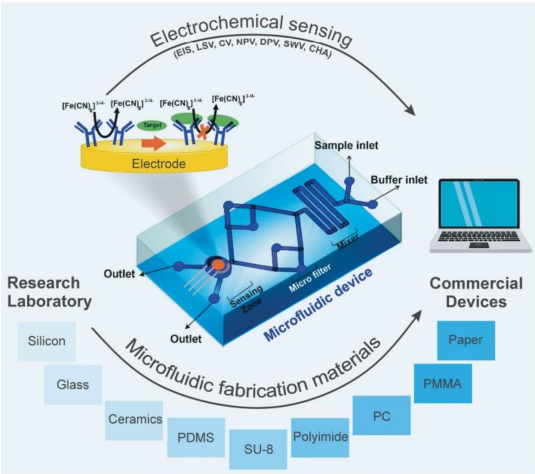

Figure 3. Illustration of the electrochemical methods and microfluidic materials employed in the design of label-free electrochemical microfluidic devices (Ebrahimi et al., 2022)

Further innovation is illustrated by Guo et al., (2024), who developed a microfluidic electrochemical sensor (COFTpTt@c-MWCNTs/SPCE) to monitor fluoxetine (FLX) in small-volume biological samples. This device employs a PDMS chip with internal microchannels that significantly reduce sample volume requirements. After optimization, the sensor obtained a low detection limit (LOD) of 24,3 ng/mL, a wide linear range, excellent reproducibility, and high selectivity, and it proved effective for FLX detection in rat serum, showcasing strong potential for point-of-care diagnostics. Complementing these advances, Srikanth et al., (2021) introduced a low-cost, droplet-based microfluidic electrochemical device fabricated via inkjet printing. This platform integrates a microfluidic T-junction with a three-electrode electrochemical system, enabling cyclic voltammetry measurements within droplets. The device successfully detected ascorbic acid under varying flow rates and concentrations, with a clear oxidation peak observed at 0.28 V under optimal conditions (2 mM concentration, 1 µL/min flow rate, and 50 mV/s scan rate). This study represents the first successful implementation of cyclic voltammetry in a droplet-based electrochemical microfluidic system, opening new possibilities for on-site and miniaturized analytical applications.

Following advances in microfluidics, attention has also turned to plug-and-play sensor systems that allow seamless and immediate operation without technical complexation. Plug-and-play system refers to a device and sensor component design aimed at ease of use, allowing quick connection and immediate operation once the device is connected to a computer or another platform (such as a smartphone or tablet), without the need for complex driver installation or configuration. One notable innovation in this area was introduced by Montes-Cebrián et al., (2018) designed portable Point-of-Care sensor for diagnostic systems, based on the 'Plug-and-Power' concept". In this approach, the disposable sensor not only functions as a detection element but also serves as the power source, eliminating the need for batteries in the reader unit. The reader contains only the electronics required to conduct the analysis, analyze the data, and show the result. Power is directly supplied by a paper-based test strip that incorporates an environmentally friendly, non-toxic redox chemical system. The feasibility of this concept was demonstrated using a self-powered portable glucose meter, comprising a test strip that functions as both a power source and glucose sensor (using a paper-based biofuel cell), along with a battery-free electronic reader. Tests conducted with human serum samples (glucose concentrations ranging from 5–30 mM) yielded results comparable to those of commercial devices. This approach holds great promise for broader application across various types of biosensors, supporting the decentralization of laboratory diagnostics, personalized medicine, and improved patient compliance.

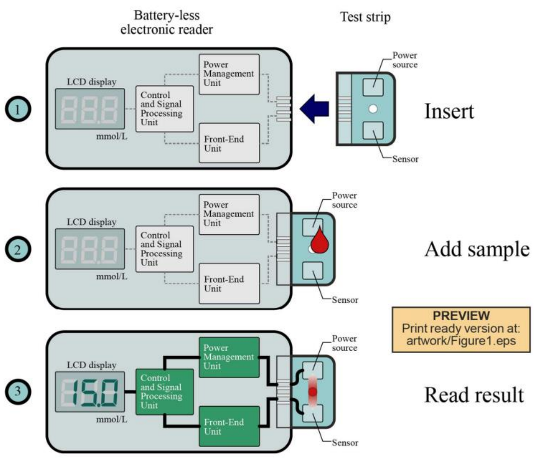

Figure 4. Functioning of the Plug-and-Power Point-of-Care diagnostic tool (Montes-Cebrián et al., (2018).

Salicylic acid (SA) plays a vital role as a phytohormone in plant stress responses and also functions as a common analgesic and anti-inflammatory drug. Accurate monitoring of SA is essential both for early detection of plant diseases and for managing potential drug overdoses in clinical settings. Kashyap & Kumar, (2021) introduced a portable, cost-effective electrochemical sensor system with a plug-and-play design, precise electronics, and robust data analysis capabilities for SA detection. The sensor demonstrated high linearity, sensitivity, and selectivity, and its accuracy was validated using real-world samples.

Building on this innovation, Jaya Lakshmi et al., (2024) developed a sustainable and low-cost miniaturized plug-and-play electrochemical sensor using stereolithography (SLA) 3D printing with biodegradable UV resin. The microfluidic platform comprises three compartments to house the electrode components and was tested for the detection of nanomolar concentrations of dopamine in biological fluids. The system employed chronoamperometry and cyclic voltammetry using a g-PLA/gold nanoparticle microelectrode. The sensor exhibited a linear detection range from 0,1 to 120 nM, a detection limit (LOD) of 0,083 nM, and a quantification limit (LOQ) of 0,27 nM, demonstrating its capacity for sensitive and eco-friendly biosensing.

IV. MINIATURIZATION AND INTEGRATION OF VOLTAMMETRIC SENSORS IN DIGITAL PLATFORMS: OPPORTUNITIES AND CHALLENGES

Recent studies indicate a strong trend in integrating miniaturized voltammetric sensors with microcontrollers and smartphones to develop efficient, user-friendly portable analytical devices. This method facilitates real-time monitoring, remote functionality, and seamless data accessibility, enhancing its applicability across diverse domains, including education, environmental surveillance, and healthcare diagnostics.

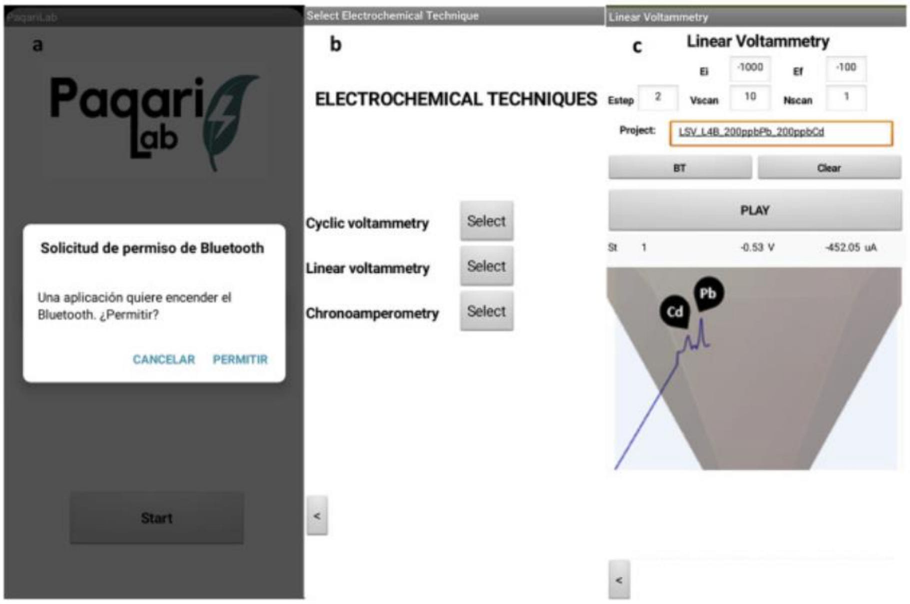

Figure 5. A screenshot of the mobile application interface for potentiostat control, showcasing (a) Bluetooth activation for device recognition, (b) selection of the electrochemical technique, and (c) parameter input along with real-time visualization of analytical measurements (Cordova-Huaman et al., 2021)

One notable example is the work by Cordova-Huaman et al., (2021), who designed a low-priced, portable electrochemical workstation, merging an open-source Arduino-based potentiostat and a smartphone application for user-friendly control of electrochemical parameters and real-time data display. Cyclic voltammetry, linear sweep voltammetry, and chronoamperometry are all supported by the potentiostat, within an operating range of ±225 μA and ±1,50 V, delivering performance comparable to commercial potentiostats. The device was demonstrated to be effective for educational purposes, such as redox identification, pencil graphite electrode characterization, and heavy metal detection.

Figure 6. Smartphone-Based Water Quality Monitoring System (Liao et al., 2020)

Another development by Liao et al., (2020) showcased the integration of an electrochemical sensor entirely made of copper components—including the working microelectrode (Cu), counter electrode (Cu), and reference electrode ($Cu/CuCl_2$)—with a smartphone platform for in-situ quantification of Pb^{2+} ions and COD in water quality analysis. The system includes a lightweight handheld detector (~50 g) able to conduct several electroanalytical methods, including chronoamperometry, cyclic voltammetry, square wave voltammetry, and linear sweep voltammetry. The results are visualized in real-time on a smartphone app, while contamination data and geographic locations are accessible via a Cloud-based map platform, allowing public data sharing. This smartphone-based system, with its portability, low cost, compact size, and full wireless capability, holds significant potential for noninvasive detection of cancer biomarkers (miR-21) in saliva, particularly in resource-limited settings. Interface innovation is also a key focus. A smartphone-based biosensing system for electrochemical detection of miR-21 was developed by Shin Low et al., (2020), utilizing screen-printed disposable biosensors modified with rGO/Au, a custom circuit board, and an Android application.

However, the process of miniaturizing and digitally integrating voltammetric sensors introduces several technical challenges, particularly concerning signal noise, sensor stability, and battery efficiency. Sensor miniaturization often weakens signal strength, making it more susceptible to electronic and electrochemical noise. For instance, Bianchi et al., (2020) proposed a budget-friendly, mobile Wi-Fi potentiostat that simplifies data handling by eliminating the need for additional processing hardware. However, it exhibited a relatively high noise level (6.5 nV/√Hz at 10 kHz). Power efficiency is also critical for portable and wearable devices. Batteries must be small enough for portability yet capable of supporting sensor and electronic operation over extended periods. This issue was addressed in a study by Xue et al., (2023), who designed a low-power sensor for simultaneous measurement of Pb^{2+} and Cu^{2+} in groundwater, achieving low detection limits and high precision, showing strong potential for on-site environmental monitoring.

V. APPLICATIONS IN POINT-OF-CARE TESTING

The application of miniaturized voltammetric sensors integrated with microcontrollers and smartphones demonstrates substantial potential across diverse sectors, particularly in the context of Point-of-Care Testing (POCT). In the medical field, these portable systems have been effectively utilized for swift and non-invasive detection of essential biomarkers. For example, Promsuwan et al., (2023) developed a smartphone-enabled glucometer that leverages Near Field Communication (NFC) for wireless operation of a compact glucose biosensor. This setup integrates a smartphone with an NFC compatible potentiostat connected to a screen-printed carbon electrode enhanced with Prussian blue-graphene ink and gold nanoparticles containing glucose oxidase. The device demonstrated remarkable precision, detecting glucose concentrations between 0,5 and 500 μM, with a detection limit of 0,15 μM, offering performance comparable to clinical-grade methodologies. Similarly, Bayoumy et al., (2024) presented a point-of-care (POCT) electrochemical sensor for uric acid. This sensor used pencil graphite electrodes (PGE) treated with polydopamine (PDA) and gold nanoparticles (Au-NPs), and it showed a linear response between $5{,}0 \times 10^{-5}$ and $5{,}0 \times 10^{-4}$ mol L^{-1}, a detection limit of 1.\,57 × 10^{-5} mol L^{-1}, and accurate, repeatable results in human urine. For cancer diagnostics, Pacheco et al., (2018) designed a voltammetric sensor using molecularly imprinted polymers (MIPs) to detect the breast cancer biomarker CA 15-3. The sensor was fabricated by imprinting CA 15-3 onto a screen-printed gold electrode via protein adsorption and electropolymerization of 2-aminophenol. This sensor was fast (15 minutes), detection limit of 1,5 U mL^{-1}, inexpensive, disposable, and suitable for POCT integration. For the detection of the COVID-19 spike (S) protein, Beduk et al., (2021)) designed a single-use electrochemical biosensor utilizing laser-scribed graphene (LSG) and three-dimensional gold nanostructures functionalized with cysteamine and EDC:NHS. The sensor exhibited range of 5,0–500,0 ng/mL, with a detection limit of 2,9 ng/mL, validated using patient blood samples. Integrated with a custom-built mini potentiostat and the KAUSTat smartphone app, this platform offered rapid (~1 hour), affordable, and easy-to-use diagnostics suitable for remote or self-monitoring use.

For environmental monitoring, small voltammetric sensors provide affordable and easy-to-use ways to detect dangerous pollutants like heavy metals and pesticides directly in the environment. Xu et al., (2020) designed a POCT system capable for the simultaneous detection of Cd^{2+}, Cu^{2+}, Hg^{2+}, and Pb^{2+}, using custom-designed electrodes. The system provided low detection limits (0,025–0,351 μM) and a wide dynamic range (0,10–12,5 μM) via differential pulse voltammetry (DPV). It featured a handheld analyzer (~$10, ~30 g, ~253 mW) that communicated bi-directionally with a smartphone via a custom DHMI app, allowing real-time voltammogram display. The sensor's performance in water samples closely matched results obtained by ICP-MS, making it highly effective for on-site monitoring in low-resource environments. Meanwhile, Maraprasertsak et al., (2021) developed a low-cost, non-enzymatic electrochemical sensor for detecting organophosphate pesticides, screen-printed carbon electrodes enhanced with copper oxide nanostructures and integrated with an NFC-enabled potentiostat for smartphone use, the system showed high sensitivity and the ability to detect pesticide residues in real vegetable samples at levels lower than 10 ppb, suggesting it's well-suited for effective pesticide screening in the field.

In the food sector, this technology has been utilized for the rapid detection of harmful contaminants and illegal additives such as formaldehyde and nitrite, ensuring consumer-level food safety. Soleh et al., (2023) developed a fully integrated smart device for on-site detection of formaldehyde (FA) in food, using a three-electrode sensor based on nanoPd@laser-induced graphene (LIG), powered and controlled wirelessly via NFC with a smartphone. The sensor exhibited a linear detection range of 0,01–4,0 mM, a detection limit of 6,4 μM, excellent reproducibility (RSD 2,0–10,1%), and strong anti-interference properties. Its results correlated well with commercial potentiostats and spectrophotometric analysis of real food samples. Promsuwan et al., (2024) further developed a portable electrochemical nitrite sensor using disposable screen-printed electrodes enhanced with nanoPd-decorated bismuth sulfide microspheres (nanoPd@Bi_2S_3MS/SPE) that are linked to a smartphone-based potentiostat. This sensor achieved a linear range of 0,01–500 μM and a detection limit of 0,0033 μM, with excellent repeatability, reproducibility, catalytic stability, and interference resistance—delivering a simple, fast, and accurate system for nitrite detection in food products.

Overall, the integration of miniaturized voltammetric sensors with smartphone platforms opens new avenues for affordable, portable, and accurate POCT devices. These systems offer real-time, accessible diagnostics for critical applications in healthcare, environmental safety, and food quality control, especially in areas with limited access to resources.

VI. RECENT PLATFORMS AND DEVICES

Recent developments in platforms and portable voltammetric devices show a strong trend toward miniaturized, cost-effective, and connected systems. Reviews of current technologies highlight significant advancements in voltammetry-based electronic tongues (e-tongues), which mimic the human taste system using arrays of non-specific chemical sensors that generate response patterns. These patterns are analyzed through multivariate statistical methods to differentiate and categorize complex liquid samples, such as beverages. Like the human taste system, e-tongues rely on non-selective sensing elements that transmit signals to a processing unit—typically a computer equipped with pattern recognition software. Almario et al., (2024) introduced an intelligent e-tongue that utilizes a polypyrrole sensor array for the rapid analysis of various Arabica coffee varieties: Typica, Bourbon, Maragogype, Tabi, and Caturra. The device, equipped with seven electrodes and a portable potentiostat controlled by a smartphone, underwent testing and analysis using Principal Component Neural Network (PCNN) and Cluster Analysis (CA). The results indicated that the polypyrrole sensors produced unique electrochemical "fingerprints" for each coffee type, demonstrating the e-tongue's utility as a fast, inexpensive, and portable instrument for assessing coffee quality and identifying adulteration in the food and beverage industry.

In addition, the development of portable voltammetric tools increasingly involves open-source platforms such as Arduino and Raspberry Pi. Kremers et al. (2020) introduced PortaDrop, a portable microfluidic digital system utilizing Raspberry Pi, designed to conduct various chemical and electrochemical tests on electronically manipulated droplets. Though still in its prototype phase, PortaDrop is designed for adaptability, integrating sample preparation processes—such as mixing and dilution—with built-in electrochemical sensors. Its applications include heavy metal detection through voltammetry and reconfigurable potentiometric sensing. Unlike conventional single-target contaminant detection systems, PortaDrop offers a modular approach, allowing a single device to conduct multiple water quality tests—such as sequential analyses for lead, copper, and cadmium—by modifying the microfluidic sequence and sensor configuration. Furthermore, Gao et al., (2021) demonstrated the development of a homemade Arduino-based potentiostat for hydrogen peroxide detection. This low-cost, highly flexible system was capable of performing chronoamperometry and cyclic voltammetry with high accuracy and precision. Its sensing performance was found to be nearly equivalent to that of commercial potentiostats, indicating strong potential for the construction of various electrochemical sensing systems. This innovation could pave the way for the development of advanced sensing platforms for medical diagnostics and environmental monitoring.

Microcontroller-based device is typically equipped with a simple user interface and the capability to perform basic voltammetric techniques. Furthermore, integration with the Internet of Things (IoT) enables wireless data transmission to cloud platforms for remote storage and analysis, facilitating real-time monitoring and efficient data sharing. In a recent study, a homemade electrochemical IoT-enabled device was developed for the simultaneous detection of pharmaceutical compounds such as paracetamol, salicylic acid, and carbamazepine in aquatic environments, using carbon screen-printed electrodes and differential pulse voltammetry (DPV). The device was validated using potassium ferricyanide and demonstrated performance comparable to benchtop potentiostats (Queijo et al., 2025).

VII. FUTURE DIRECTIONS AND DEVELOPMENT PROSPECTS

The future direction and development prospects of portable and integrated voltammetric sensors are highly promising, driven by rapid advancements across multiple scientific and technological disciplines. One of the key development areas is the utilization of nanomaterials such as gold nanoparticles (Anh et al., 2024; Sabitova et al., 2024), graphene (Naghshgar et al., 2024; Zheng et al., 2025), and carbon nanotubes (Z. Shi et al., 2025), which can significantly enhance the sensitivity, selectivity, and stability of sensors by increasing the active surface area and electrical conductivity. In addition, biosensors designed based on biomolecular interactions are progressing rapidly, enabling highly specific analyte detection with excellent sensitivity. For instance, the development of miRNA-based biosensors for SARS-CoV-2 detection at point-of-care (POC) settings has demonstrated effective performance for rapid diagnostics (Mendoza et al., 2020).

Furthermore, the integration of voltammetric sensors with artificial intelligence (AI) presents vast opportunities for automated data analysis, pattern recognition, drift correction, and predictive modeling based on historical data. As demonstrated by Singh et al., (2024), an AI-based denoising autoencoder was successfully employed to eliminate noise from voltammetric data acquired using a portable potentiostat, thereby enhancing the signal quality to be comparable to that of laboratory-grade instruments. This approach significantly improves the reliability of portable sensors for rapid pathogen detection in POC settings. Additionally, the integration of these sensors into wearable and e-health systems holds substantial promise, as illustrated by Z. Shi et al., (2024), who developed a wearable biosensor for real-time monitoring of riboflavin in sweat. This system utilizes flexible electrodes based on graphene and platinum nanoparticles, along with wireless NFC-based data transmission. The findings reveal its potential applications in precision nutrition and continuous health monitoring. Ultimately, realizing the full potential of this technology will require strong multidisciplinary collaboration among chemists, electronic engineers, computer scientists, and materials scientists to develop next-generation sensor designs, integrated systems, and impactful applications across various fields.

VIII. CONCLUSION

Significant advancements in voltammetric technology have driven the development of portable sensors and point-of-care (POC) devices that are increasingly sophisticated, affordable, and user-friendly. These innovations include integration with microcontrollers and smartphones, the use of functional materials such as nanomaterials and molecularly imprinted polymers, and the miniaturization of electrochemical systems that enable rapid, accurate, and in situ detection of various important analytes. Its broad applicability across healthcare, environmental monitoring, and food safety demonstrates that portable voltammetry has become a key component in transforming diagnostic and analytical paradigms.

Nonetheless, several challenges remain, including the need for broader clinical and analytical validation, improved sensor stability and selectivity in complex matrices, and the development of truly user-friendly platforms. Future research should focus on multi-analyte integration, system automation, and the incorporation of artificial intelligence and Internet of Things (IoT) technologies for enhanced data processing and connectivity. By overcoming these challenges, voltammetric sensing in portable and POC devices can evolve into a central tool in the era of precise and inclusive digital diagnostics.

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