bacteria

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Review

Electrochemical Sensors Development for Bacterial Detection and Surveillance: Recent Advances and Future Directions

Baljit Singh [1,2,*] and Kamna Ravi [2]

[1] MiCRA Biodiagnostics Technology Gateway, Technological University Dublin (TU Dublin), D24 FKT9 Dublin, Ireland
[2] Health, Engineering & Materials Science (HEMS) Research Hub, Technological University Dublin (TU Dublin), D24 FKT9 Dublin, Ireland
* Correspondence: baljit.singh@tudublin.ie; Tel.: +353-1-220-7863

Abstract

In today's environment, rapid, reliable, and accurate bacterial detection is essential for protecting public health while preserving and ensuring the safety of food, water, and agricultural and environmental systems. Over the years, electrochemical sensors have gained widespread attention as viable candidates due to their rapid response, high sensitivity and selectivity, adaptability and portability, and low manufacturing cost. This facilitates their integration into various sectors, including healthcare and diagnostic applications, food safety and agriculture, and water and environmental monitoring. While these achievements represent tremendous progress, some of the challenges that need to be overcome include stability, batch-to-batch reproducibility, manufacturability, performance reliability, and the lack of point-of-care (POC) implementation for the utilization of these sensors for real-sample bacterial analysis. However, in the future, it is expected that with continued efforts made towards improving durability, standardization, and manufacturability, electrochemical bacterial sensors will be pivotal to the advancement of efficient bacterial diagnostics across various fields. This review presents major developments in modern electrochemical sensing technologies, which include, but are not limited to: electrochemical sensor and biosensor surface modifications, nanomaterials, the integration of artificial intelligence (AI) and machine learning (ML), and the emergence of wearable systems, for bacterial detection and monitoring. Additionally, their utilization in the aforementioned sectors is discussed. The integration and sustained use of these advanced electrochemical sensors for bacterial detection and surveillance can significantly enhance global safety and public well-being.

Keywords: electrochemical sensors; bacterial detection; health and diagnostics; food safety; agriculture; water and environment monitoring; point-of-care (POC); artificial intelligence (AI); machine learning (ML)

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1. Introduction

Bacterial contamination is a major global challenge affecting human and environmental health, making it a critical issue in the pursuit of sustainability in areas such as regulation, monitoring and maintenance. The increase in the occurrence of pathogenic and opportunistic bacteria in healthcare, agricultural, food, and environmental systems is a major reason for the rapid increase in infectious diseases [1–3]. Species such as *Escherichia coli*, *Salmonella species*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Listeria monocytogenes*,

and *Vibrio* spp. cause a variety of diseases ranging from minor gastrointestinal diseases to serious diseases like pneumonia, meningitis, septicemia, and toxic shock syndrome. The capacity of bacteria to form biofilms and to express antimicrobial resistance (AMR) complicates the control and management of bacterial infections [4–9].

The spread of bacterial contamination is influenced by a variety of factors, such as socio-environmental and technological factors. The indiscriminate use of antibiotics in medical and agricultural practices has led to the emergence of AMR, while the high growth rate of the population and urbanization have added pressure to the health infrastructure, especially in metropolitan cities [10–12]. In addition, globalization and food supply chains have led to an increased risk of food products being exposed to different environmental and handling conditions during production, processing, storage, and transportation [13–15]. In agricultural settings, excessive use of chemicals such as fertilizers may contribute to bacterial growth. Untreated water sources such as surface water, groundwater, and raw water systems are still significant bacterial growth media, particularly in areas where filtration and water treatment are not readily available [16,17]. In addition, environmental factors such as temperature variation, precipitation, the accumulation of organic matter, and natural disasters can contribute to the survival and spread of bacteria, thus raising the risks of bacterial contamination and complicating the management of product quality [18].

It is generally believed that the commonly used bacterial detection methods, such as culture-based tests, ELISA, and PCR, are the "gold standard" in bacterial diagnosis in terms of sensitivity and specificity. Although culture-based tests are still important for AMR diagnosis, the longer incubation period, ranging from hours to days, can cause a delay in the corresponding responses to bacterial contamination [19]. Optical sensing techniques such as fluorescence detection, as well as absorbance detection, have shown promising capabilities in the development of a rapid response system, which has the ability to be highly sensitive. Raman spectroscopy has also been identified as a promising approach to the development of a label-free detection system for bacterial identification. However, these techniques have shown a number of drawbacks, such as high costs of operation, environmental interference, as well as the need to invest in specialized equipment. PCR-based molecular detection has shown promising capabilities in the detection of low concentrations of pathogens, but the approach has shown a number of drawbacks, such as the complex sample preparation requirements, the need to prevent contamination, as well as the high costs associated with the approach. Immunoassays have shown promising capabilities in pathogen detection due to their high sensitivity, but certain drawbacks, such as the need to invest in labor-intensive multi-step processing and nonspecific binding effects prove to be major limitations for point-of-care (POC) deployment [20].

In the recent past, electrochemical sensing technology has gained popularity due to the simplicity of operation, efficient signal transduction, and versatility, as well as the suitability for bacterial detection in POC settings [21]. The advancements achieved in the fields of materials science, nanotechnology, surface science, and biofunctionalization have improved the performance characteristics of electrochemical sensors for bacterial detection purposes [22]. Additionally, the integration of microfluidics, lab-on-a-chip technology, Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), geographic information systems (GIS), and wireless communication has increased the functionality of electrochemical sensors for bacterial detection purposes [23,24].

Despite these advances, issues related to the manufacturability, stability, and practical application of electrochemical sensing technology have not been fully resolved. Further development in regulation, funding, and interdisciplinary collaborations may help to translate laboratory-based developments into practical applications [25–27]. From a translational

perspective, electrochemical sensing technology must be viewed under the umbrella of regulatory compliance, data integrity, sustainability, and integration. The transition of electrochemical sensing technology from prototype to widely available POC technology must be achieved through compliance with safety regulations and validation protocols. To achieve technological advancement in the field of electrochemical sensing technology, there must be integration of experts from various fields, ranging from materials science and engineering to medicine, microbiology, and data science, to ensure the technology is technically viable and clinically relevant to various applications [28].

Furthermore, the issue of sustainability is becoming increasingly important in the development of sensors, including the efficiency of large-scale manufacturing processes, the use of resource-saving materials, sensor reusability, and the environmental impact of the electrochemical sensors. Thus, it is vital to promote the active development of sustainable electrochemical sensors for bacterial monitoring across various sectors. Modifications and enhancements, such as utilizing biorecognition molecules, i.e., antibodies, aptamers, and enzymes to improve sensor specificity, are facilitated due to electrochemical sensors being rapidly evolving analytical tools. However, the development of bioreceptor-free electrochemical sensors is also being considered to reinvent sustainability and ease of manufacturing (by reducing production costs) of these sensors in the future. This review summarizes and evaluates the recent developments in electrochemical sensors modified and adapted for bacterial detection and monitoring in various sectors and the overall implications in the promotion of global health and sustainability.

2. State-of-the-Art Electrochemical Sensors

Electrochemical sensors are often divided into classes depending on their recognition elements or the electroanalytical transduction techniques. Depending on the bioreceptor used, they can be enzyme-based, antibody-based (immunosensors), DNA- or RNA-based (genosensors), whole-cell, and bacteriophage-based sensors. Each category has brought unique advantages regarding selectivity, robustness, and suitability to specific analytical targets, e.g., intact bacterial cells, nucleic acids, or metabolic products. In terms of transduction, electrochemical bacteria detection is mainly based on amperometric, voltammetric, potentiometric, impedance-based, and capacitance-based methods [29]. Figure 1 presents the various components that are involved in electrochemical bacterial detection, including the various nano-functional materials, analytical sample types, biosensing probe molecules, and transducer components.

Amperometry and voltammetry are common methods to analyze bacterial activity or metabolite production at a constant potential. Voltammetric techniques such as cyclic voltammetry (CV), linear sweep voltammetry (LSV), differential pulse voltammetry (DPV), and square-wave voltammetry (SWV) are basically used to study the redox processes related to bacterial metabolism, redox-active labels, or reporter molecules. Among these, DPV and SWV are especially appreciated for their sensitivity and low detection limits due to their ability to reduce background currents [30–32].

In the electrochemical biosensing field, electrochemical impedance spectroscopy (EIS) has recently become one of the most widely used methods for bacterial sensing. It is a highly sensitive and label-free method that allows detecting bacterial adhesion, biofilm formation, or biorecognition events on the electrode surface through changes in charge-transfer resistance and interfacial capacitance, thus enabling real-time monitoring [33,34]. Being nondestructive and compatible with complex samples, EIS can also be very useful for clinical diagnostics, food safety, and AMR assessments. In addition to that, photoelectrochemical (PEC) biosensors have been recognized as a highly attractive alternative sensing platform to traditional electrochemical techniques, which still lead the current market.

PEC sensors utilize light to excite semiconductors to create photocurrents, implying that the excitation signal (light) and the detection signal (electric current) are separated both temporally and spatially. As such, the sensitivity of PEC biosensors is greatly enhanced through the drastic reduction in noise signals, allowing for ultra-sensitive detection of bacteria. They are also characterized by low levels of background noise from complex matrices, allowing for accurate control of the excitation source itself, thus enhancing selectivity and reproducibility [35,36]. Electrochemical capacitance-based techniques have also proven their capability not only for bacterial detection but also real-time bacterial metabolism evaluation, which emphasizes the flexibility of electrochemical platforms. However, unlike PEC sensors, capacitance-based techniques are solely dependent on the electrical properties at the electrode interface, which are more prone to nonspecific binding and environmental variations [37].

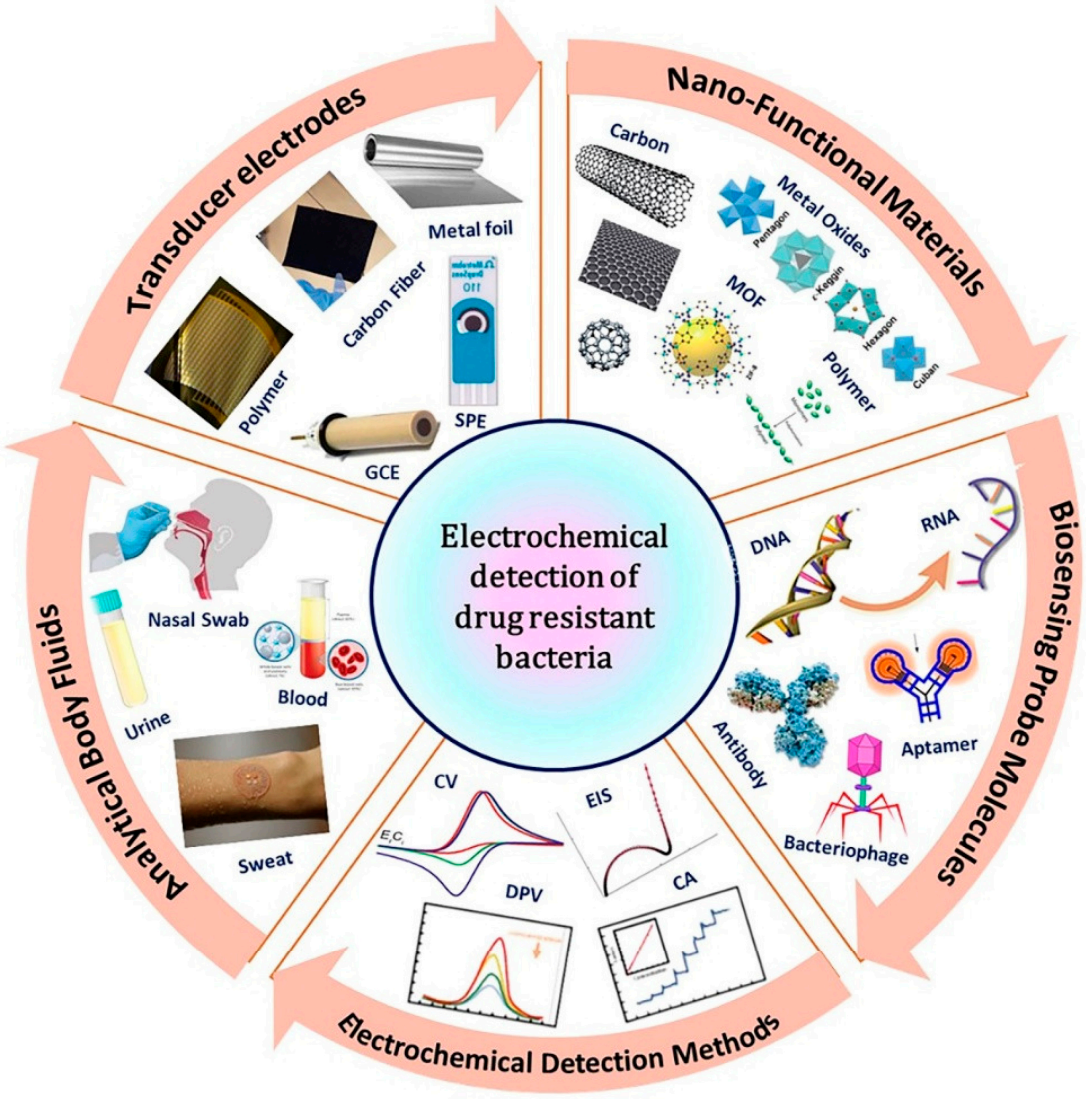

Figure 1. Electrochemical detection of drug-resistant bacteria [29]. Reprinted from Ref. [29] (Pharmaceuticals, MDPI), © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

One of the major advancements in electrochemical diagnostics can be attributed to the use of advanced and highly selective biorecognition elements. Antibodies are still the most common biorecognition elements due to their high affinity and specificity. However,

aptamers are now being more widely preferred because they are chemically more stable, more reproducible, easier to modify, and more resistant to harsh environmental conditions [38,39]. Bacteriophages and phage-derived proteins are also being used extensively for whole-cell recognition, giving them unparalleled selectivity toward live bacteria even in complex mixtures. Enzyme- and nucleic acid-based tools are still very important in the detection of bacterial metabolites, virulence factors, and resistance genes, which is helpful for rapid pathogen identification and antimicrobial susceptibility testing [40,41]. Research has mostly been focused on reusable sensing probes that are capable of multiple analyses simultaneously. This has been made possible by the optimization of immobilization chemistries in conjunction with antifouling surface modifications that result in improved operational stability, multiplexing, and reproducibility [42]. Probably one of the most important advancements in electrochemical bacterial sensing over the last ten years is the use of nanomaterials. Nanomaterials in the form of gold and silver nanoparticles, carbon nanotubes, graphene and its derivatives, quantum dots, as well as metal–organic frameworks (MOFs), and conductive polymers have been the first choice to boost sensor performance. They help to increase the effective electrode surface area, speed up the rate of electron transfer, and create a favorable environment for biomolecule immobilization. Hybrid nanocomposites, combining multiple constituents including metallic, carbon-based, and polymeric components, commonly demonstrate synergistic effects with high sensitivity and lower detection limits, thus fulfilling the major criteria for diagnostics that are clinically and environmentally relevant. Moreover, nanomaterial-enabled architectures have paved the way for the creation of ultra-sensitive, low-power, highly miniaturized sensors that can easily be taken to POC and field-deployable settings [43–45]. A summary of various sensing approaches along with their key characteristics has been outlined in Table 1.

Table 1. Commonly used electrochemical sensing approaches for bacterial detection: summarizing key features, working principles, advantages, and limitations.

Sensing Approach	Working Principle	Key Features and Advantages	Key Limitations	Ref.
Technique-based classification				
Voltammetric Sensors	Current–potential response	High portability; moderate pretreatment; medium readiness; high sensitivity; easy miniaturization	Fouling and matrix effects	[30,31]
Amperometric Sensors	Fixed-potential current response from redox activity	Excellent portability; minimal pretreatment; high readiness; rapid responses; easy integration into portable devices	Limited intrinsic selectivity without biorecognition	[31,32]
Electrochemical Impedance Spectroscopy (EIS)	Impedance change from binding events	Emerging portable implementations; often needs enrichment; medium readiness, label-free; real-time binding monitoring	Requires advanced signal analysis	[33,34]
Potentiometric Sensors	Potential difference-based sensing	Highly portable; minimal pretreatment; high readiness, simple with low power	Lower sensitivity; limited multiplexing	[35]

Table 1. *Cont.*

Sensing Approach	Working Principle	Key Features and Advantages	Key Limitations	Ref.
Biorecognition-based classification				
Aptamer-Based Electrochemical Sensors	Target aptamer recognition with electrical signal	Portable designs feasible; often needs sample cleanup; low-medium readiness, excellent specificity; adaptable	Aptamer stability issues in matrix	[37]
Electrochemical DNA/Genosensors	Electrochemical detection of nucleic acid sequences	Sequence-level specificity; pathogen strain identification and genetic marker detection; multiplexed analysis	Nucleic acid extraction or amplification required; complex assay design	
Immunosensors (Electrochemical)	Antibody–antigen induced signal change	Portable formats available; moderate pretreatment; medium-high readiness, high selectivity; clinical relevance	Antibody storage and reliability constraints	[38]
Molecularly Imprinted Polymer (MIP) Sensors	Synthetic recognition sites	High portability; minimal biological pretreatment; medium readiness, stable; reusable; cost-effective	Lower biorecognition specificity than biomolecules	[39]
Phage-Based Recognition Sensors	Bacteriophage specificity with electrochemistry	High selectivity; portable prototypes; emerging readiness, natural target specificity; stable binding	May need phage production infrastructure	[40,41]
Target-based classification				
Whole-Cell Sensors	Surface biorecognition through cell–surface interaction	Direct detection; rapid response; label-free potential; portable implementation; receptor-mediated species/strain selectivity	Nonspecific adsorption; matrix interference; fouling effects	[31]
Component/Metabolite Sensors	Molecular component detection using probes and other metabolites	High analytical specificity; very low detection limits; potential for multiplexed sensing; suitable for virulence or strain-level identification	Sample preprocessing; lack of differentiation capabilities; assay complexity	[32]
Hybrid approaches				
Integrated EC-SERS Sensors	Electrochemical + surface-enhanced Raman for dual readout	Advanced lab integration; early readiness; combines chemical and optical contrast; high specificity	Complex instrumentation; not fully portable	[42]
Integrated EC- PCR and CRISPR/Cas12a Sensors	Combination of nucleic acid amplification with CRISPR/Cas12a-mediated target recognition	Ultra-high analytical specificity; excellent sensitivity; suitable for trace pathogen detection	Requires thermal cycling; complex assay workflow; instrumentation and operational requirements	[43]

Label-free electrochemical sensing has gained significant attention among researchers as it avoids the secondary labels or enzymatic amplification steps, which in turn makes the assay less complicated and inexpensive. Such platforms allow for quicker detection and better analytical accuracy as they entail the direct transfer of bacterial binding or activity into electrical signals without the intervention of any labels [46]. Furthermore, hybrid sensing systems combining electrochemical detection with optical, magnetic, or microfluidic elements have also been developed to achieve higher analytical performances. These multimodal setups facilitate more robust analysis of complex biological or food samples, better signal validation, and greater resistance to environmental interferences. During the period of 2020–2026, a significant breakthrough was also recorded in the development of flexible, wearable, and disposable electrochemical sensors for continuous or on-site bacterial monitoring. High-throughput production techniques like screen printing,

inkjet printing, aerosol jet printing, and laser-induced graphene patterning have made it possible to manufacture electrodes at a low cost on polymeric, paper-based, or textile substrates [47,48]. There is a rising trend of using such sensors for wound infection monitoring, smart food packaging, water quality assessment, and environmental surveillance applications [49,50]. Additionally, various electrochemical detection techniques can be classified as green techniques since they do not require the use of toxic chemicals, as in the case of traditional techniques. The combination of electrochemical sensing, flexible electronics, and wireless data transmission is changing the scene at a fast pace and turning electrochemical sensors into primary elements of the next-generation smart diagnostic and monitoring systems.

Although many of the electrochemical bacterial sensors are generally versatile in their applicability to a variety of samples, their performance is generally characterized in a particular context of application. Sample matrices, background microbiota, optimization environments, and operational needs all play a significant role in the design, tailoring of the sensor surfaces, and validation of the sensor performance in each of the respective domains, as discussed in the following sections, without implying any exclusivity of the sensor in a particular domain of application.

3. Electrochemical Sensor Advancements

3.1. Health and Diagnostics

In healthcare and clinical diagnostics, the most commonly occurring bacterial pathogens are Gram-negative bacteria, including *P. aeruginosa*, *Acinetobacter* spp., *Enterobacter* spp., *Burkholderia cepacia* complex, *S. maltophilia*, *Ralstonia pickettii*, *Sphingomonas paucimobilis*, and *E. coli*, as well as Gram-positive bacteria, including methicillin-resistant *S. aureus* (MRSA), Enterococci, and *S. pneumoniae*. Opportunistic non-fermenters, including *Serratia marcescens*, are also commonly implicated [51–54]. These microorganisms often have a close association with diagnostic samples, nosocomial infections, and contaminated clinical environments. The need for rapid, sensitive, and selective detection directly in complex matrices, i.e., blood, urine, saliva, sputum, and wound exudates, has led to major developments in electrochemical biosensors.

The early developments in electrochemical biosensors have mainly concentrated on impedance- and voltammetry-based whole-cell detection strategies, which have shown proof-of-concept applicability for clinical samples. For instance, Eskandari et al. developed a flexible, printed impedance-based electrochemical sensor incorporating a screen-printed Ag/AgCl electrode in a dentated spiral configuration for the nonspecific *E. coli* detection in wound exudates. The device achieved a detection limit of 10^2 CFU/mL and enabled discrimination across a broad concentration range of 10^2–10^7 CFU/mL, highlighting its suitability for complex biological fluids [55]. Similarly, Kumar et al. reported a glassy carbon electrode modified with rGO-liposome (GCE-L-rGO) for specific *E. coli* detection, achieving a sensitivity of ~26 µA per 10^6 cells/mL within a range of 3×10^3 to 3×10^4 cells/mL [56]. While these systems demonstrated reliable quantification, their detection limits remained within the 10^2–10^3 CFU/mL range, reflecting the performance typical of earlier nanomaterial-assisted platforms.

Subsequent advances incorporated molecular recognition layers and nanostructured interfaces to improve both sensitivity and selectivity. Rapichai et al. reported a nanoMIPs-based electrochemical sensor employing a gold screen-printed electrode (AuSPE) functionalized with a self-assembled monolayer of 16-mercaptohexadecanoic acid (MHDA) for specific *S. epidermidis* detection. Using EIS, the system achieved a detection limit as low as 1 CFU/mL and a linear range of 10^1–10^6 CFU/mL [57]. This was a significant step forward with regard to analytical sensitivity compared to the previously developed whole-cell

detection systems. Recent developments have been focused on the development of highly selective strategies for biorecognition, such as immunosensors, aptasensors, and bacteriophages, for the detection of either whole bacterial cells or particular virulence-associated markers. In addition, the incorporation of microfluidic devices has enabled the preprocessing, enrichment, and detection of samples, reducing the time required for the assays and enhancing the analytical reproducibility. An impedimetric sensor capable of specifically detecting *E. coli*, *S. aureus*, and *Vibrio parahaemolyticus* demonstrated reliable quantitative detection over a concentration range of 1.0×10^1 to 1.0×10^6 CFU/mL within 40 min. Notably, six EIS-derived parameters were extracted to construct a ML dataset, improving classification robustness and quantitative accuracy [58]. The incorporation of ML represents a shift from single-parameter impedance measurements toward multidimensional signal analysis, enhancing diagnostic reliability in complex matrices.

Further improvements in specificity and real-sample applicability were achieved through advanced nanocomposite functionalization. Dilmani et al. reported a label-free impedimetric sensor based on a bacteriophage receptor-binding protein peptide and MXene-AgNP nanocomposite-modified screen-printed carbon electrode (SPCE) for selective *S. aureus* detection in human serum and urine. The platform demonstrated a broad linear detection range (10–10^6 CFU/mL) and a low detection limit of 2.78 CFU/mL, confirming improved matrix tolerance and clinical relevance [59]. In addition to whole-cell detection, electrochemical biosensors have expanded toward host-response biomarkers associated with bacterial infection. Shi et al. developed a dual-channel electrochemical aptasensor modified with Ti_3C_2Tx-PB/Chit/AuNPs for simultaneous specific detection of C-reactive protein (CRP) and interleukin-6 (IL-6), inflammatory markers produced during *E. coli* and Group B Streptococcus (GBS) infections. The system achieved linear detection ranges of 0.1–15 μg/mL for CRP and 0.01–100 ng/mL for IL-6, demonstrating the growing trend toward multiplexed and indirect infection diagnostics [60].

Although initial electrochemical devices were limited to laboratory environments, current advances in the field are shifting focus to portability, decentralization, and real-time analysis. POC devices, including those integrated with smartphones or portable potentiostats, are among the most rapidly developing areas in healthcare diagnostics. These devices are characterized by short analysis times, low sample volume requirements, and ease of use, making them highly valuable in resource-constrained environments and outbreak situations. Jo et al. reported a rapid wireless electrochemical biosensor employing colistin- and vancomycin-conjugated polymer dot-coated electrodes (PD-Colis and PD-Vanco) with smartphone-based monitoring for specific, whole-cell detection of pneumonia pathogens in human sputum. The system achieved detection limits of 3.1 CFU/mL for Gram-positive bacteria and 3.0 CFU/mL for Gram-negative bacteria and was further applied to specifically detect carbapenem-resistant *K. pneumoniae* (CRKP) and MRSA [61]. These results demonstrate laboratory-level sensitivity within a portable diagnostic format. Similarly, Li et al. reported an electrochemical sensor based on a two-dimensional material MXene, multi-walled carbon nanotubes, and polyvinyl alcohol ($MWCNTs_{0.6}$/$MXene_{0.4}$/PVA) composite hydrogel for the detection of biomarkers like pyocyanin (PCN), uric acid (UA), and histamine (HA): biomarkers signifying *P. aeruginosa* infection, in simulated wound exudates. The detection limit of the reported sensor was decreased to a range of 0.84~0.98 μM. This study offers a high-precision and multi-parameter integrated approach for POC detection of wound infections (Figure 2) [62].

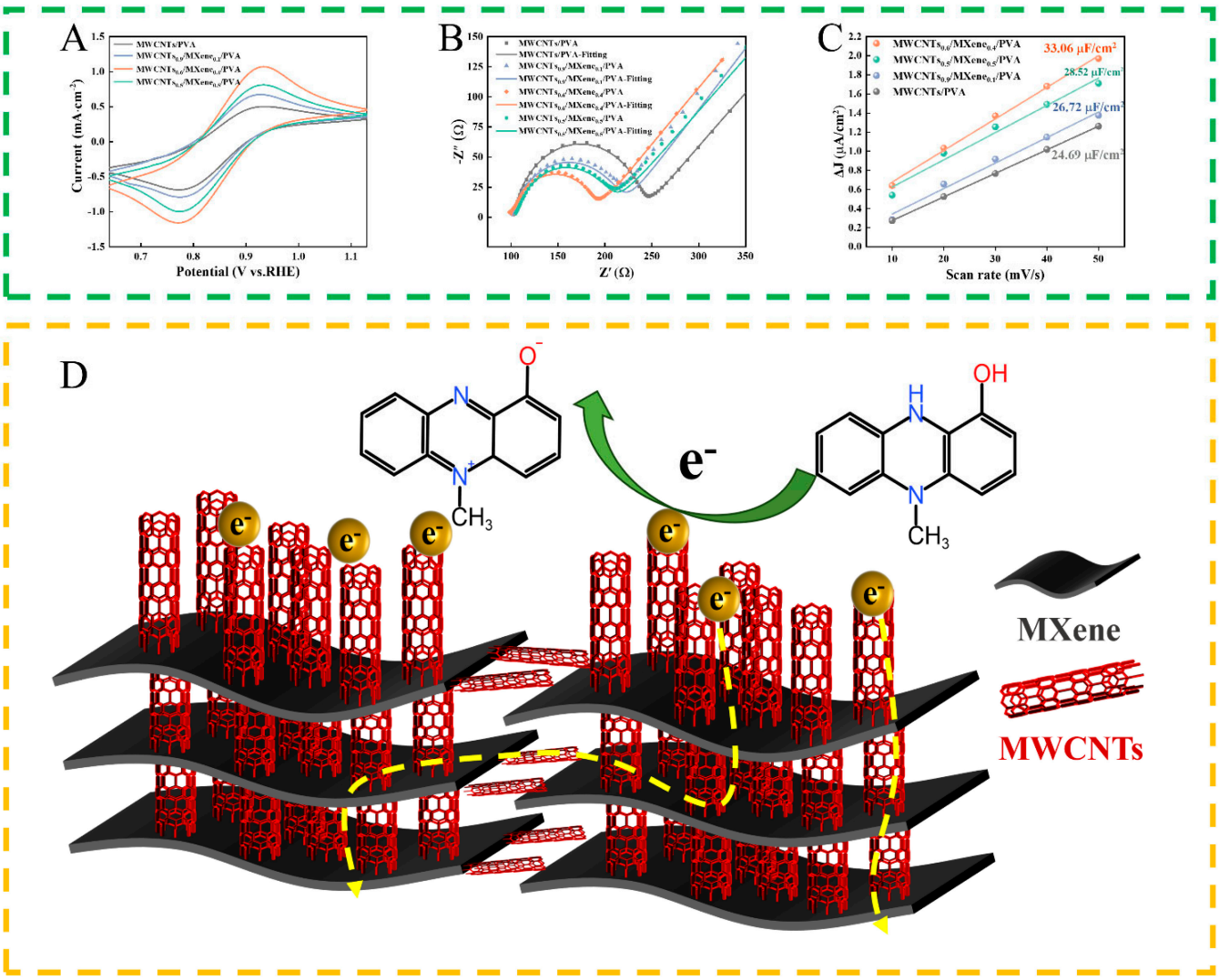

Figure 2. Electrochemical performance characterization of the MWCNTs/MXene/PVA series sensors was conducted in a 0.1 M KCl solution containing 5 mM $[Fe(CN)_6]^{3-/4-}$. (**A**) CV characterization; (**B**) EIS characterization and fitting outcomes; (**C**) graph of the current density difference in a series of sensors as a function of scan rate; (**D**) schematic diagram of the carrier transport mechanism of the $MWCNTs_{0.6}/MXene_{0.4}$/PVA sensor [62]. Reprinted from Ref. [62] (Micromachines, MDPI) © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Overall, the progress in the development of electrochemical diagnostic tools for bacterial detection signifies a clear advancement in technology, as evidenced by the following: detection sensitivity has been improved from the low micrometer range in initial whole-cell impedance devices to near single-cell sensitivity in nanostructured and biofunctionalized devices; selectivity has been improved from physicochemical changes to highly specific molecular recognition strategies, including the use of antibodies, aptamers, bacteriophage-derived peptides, and molecularly imprinted polymers (MIPs); and detection times have been reduced by microfluidics and ML-based data analysis. Moreover, validation in clinically relevant samples (serum, urine, sputum, wound exudates, and food samples), along with current trends in bacterial detection, including the use of multiplexing, miniaturization, smartphone integration, and POC devices, present a clear advancement in technology. This signifies a shift from a laboratory-based sensor to a real-world diagnostic tool capable of supporting the rapid management of infectious diseases and AMR monitoring.

3.2. Food Safety and Agriculture

In food production, the bacterial species found frequently include *Salmonella* spp., *Campylobacter jejuni*, *L. monocytogenes*, *E. coli* (pathogenic strains, e.g., STEC/O157:H7), *Clostridium botulinum*, *Clostridium perfringens*, *S. aureus*, *B. cereus*, and *Aeromonas hydrophila* [63,64]. These bacteria are widely documented to contaminate raw commodities, processing environments, and ready-to-eat foods. Electrochemical sensors have been widely explored for the detection of pathogenic bacteria in raw materials, processed foods, and food-contact surfaces. Albalawi et al. reported a novel electrochemical aptasensor based on multimetal perovskite (FeCoCuNiO) doped with urea-derived graphitic carbon nitride (g-C_3N_4) with a DNA-based aptamer applied to real-time specific detection of *P. aeruginosa* in beef samples. The sensor was reported to exhibit a low detection limit of 3.03 CFU/mL with high selectivity and sensitivity (Figure 3) [65].

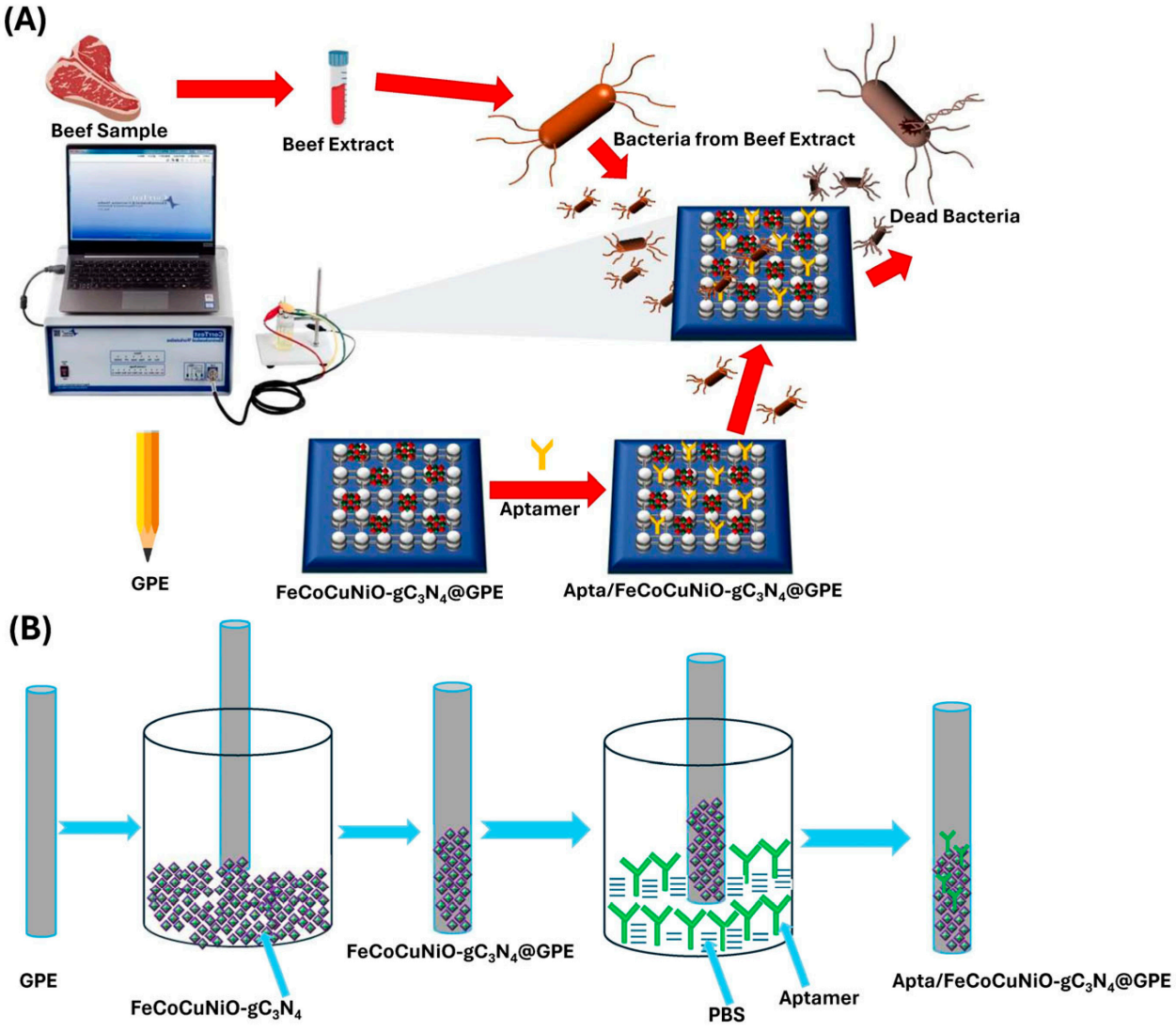

Figure 3. Scheme: (**A**) Development of *P. aeruginosa* electrochemical biosensor and its utilization for sensing in beef samples, and (**B**) fabrication of the aptasensor. [65]. Reprinted from Ref. [65] (Biosensors, MDPI) © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

A gallium-indium alloy and natural hydrogel electrochemical platform for the rapid and specific detection (30 min) of *E. coli* in complex food samples was also reported. The

results were processed by ML models. The linear range of bacterial identification was reported to be 10^2–10^9 CFU/mL with an average accuracy of 97% [66]. Liustrovaite et al. reported the application of MIPs, i.e., a non-imprinted polypyrrole (NIP-Ppy) layer and a bacteria-imprinted polypyrrole (MIP-Ppy) layer over SPCE and platinum (Pt) electrodes to design an electrochemical sensor for specific *L. monocytogenes* detection. The LOD and LOQ were reported as 70 CFU/mL and 210 CFU/mL, with a linear range from 300 to 6700 CFU/mL, respectively (Figure 4) [67]. A highly sensitive bacteriophage (T7) electrochemical sensing platform with single-wall CNT-SPE for specific *E. coli* detection on fresh leafy vegetables was reported by El-Moghazy et al. in the concentration range of 1–10^4 CFU/mL within 1 h and with high specificity [68].

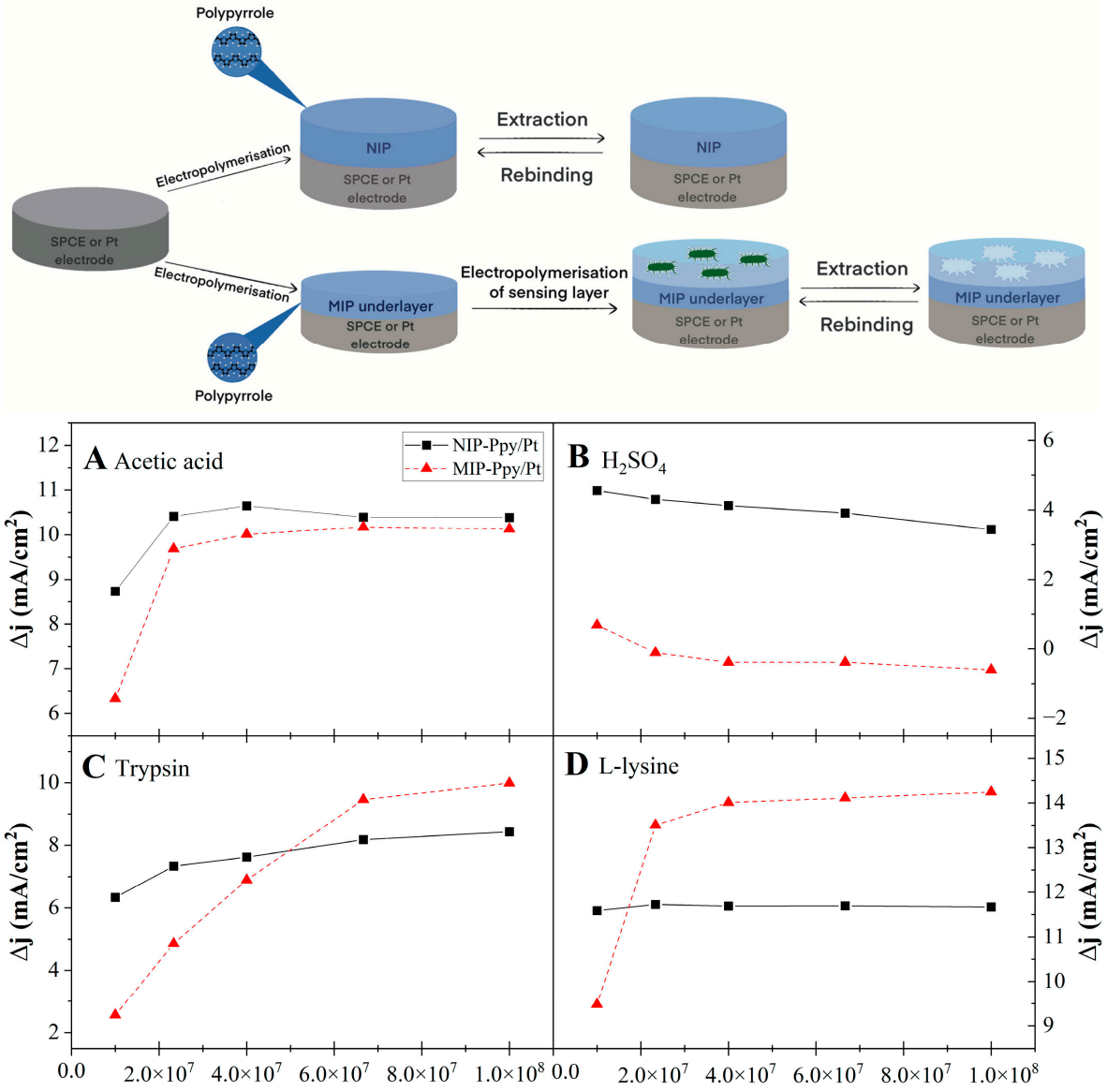

Figure 4. (**Top**): Schematic representation of electrode modification. (**Bottom**): The current density of NIP-Ppy/Pt (solid black lines) and MIP-Ppy/Pt (dashed red lines) electrodes registered using pulsed amperometric detection after incubation in solutions containing different *Listeria monocytogenes* bacteria concentrations; *Listeria monocytogenes* from MIP-Ppy was extracted using different extraction solutions: (**A**) 10% acetic acid, (**B**) 0.05 M of sulfuric acid, (**C**) 10 U/mL of trypsin, (**D**) 0.1% L-lysine [67]. Reprinted from Ref. [67] (Polymers, MDPI) © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Advances in surface modification and antifouling coatings have enabled reliable detection in complex food matrices containing fats, proteins, and carbohydrates. He et al. reported the development of electrochemical sensor, in combination with PCR and CRISPR/Cas12a (E-CRISPR biosensor), for the specific detection of *S. typhimurium* in spiked poultry meat. The linear range was reported to be 6.7×10^1–6.7×10^5 CFU/mL with an LOD of 55 CFU/mL in pure culture samples [69]. Lin et al. developed and reported a dual synthetic receptor with a bacteria-imprinted polymer film (BIF) and aptamer-electroactive 6-(Ferrocenyl)hexanethiol cofunctionalized gold nanoparticles (Au@Fc-Apt) sandwich electrochemical sensor for the specific, whole-cell detection of *S. aureus* in milk with an LOD of 10 CFU/mL [70]. Multiplexed electrochemical sensor arrays capable of simultaneously detecting multiple pathogens have been developed, enhancing throughput and efficiency in food quality control. Portable electrochemical sensors integrated into packaging or processing lines offer real-time contamination monitoring, enabling early intervention and reducing food waste. Additionally, biosensors targeting bacterial toxins and metabolites provide complementary information regarding food spoilage and safety. A ZnO/Au-based, label-free, non-Faradaic EIS platform for specific live *S. typhimurium* detection in food samples, with a detection limit of 9 CFU/mL within 5 min, was reported by Karmakar et al. [71].

In agricultural ecosystems, bacterial species found frequently include Shiga toxin-producing *E. coli (STEC)*, *Salmonella* spp., *Campylobacter* spp., *L. monocytogenes*, *Arcobacter* spp., *Yersinia enterocolitica*, *Pseudomonas* spp., and members of Enterobacteriaceae detected in leafy greens and vegetable samples (e.g., *Enterobacter cloacae*, *Klebsiella* spp.) [72]. They are found to impact soil health, irrigation water quality, crop plants, and livestock. Electrochemical sensors are increasingly used to monitor bacterial pathogens affecting crops, livestock, and soil health. In a study by Mishra et al., a portable, label-free, non-Faradaic electrochemical impedance-based sensing platform with ZnO-coated electrodes functionalized with a crosslinker for covalent antibody immobilization for the specific, simultaneous detection of *S. typhimurium* in spiked soil run-off samples was reported. The platform was reported to achieve LODs of 1 CFU/mL for *S. typhimurium* (linear range 10–10^5 CFU/mL) (Figure 5) [73].

Plant pathogenic bacteria such as Xanthomonas, Pseudomonas, and Erwinia species can cause significant yield losses if not detected early. Vatankhah et al. reported an electrochemical DNA-based biosensor with a pencil graphite electrode (PGE) modified with reduced graphene oxide (rGO) and AuNPs for specific *A. tumefaciens* T-DNA detection, which is transferred to the host cells during contamination. It was reported to display a wide linear range from 1.0×10^{-13}–1.0×10^{-9} M with an LOD of 0.87×10^{-13} M toward target DNA detection specifically [74]. Additionally, electrochemical sensors have also been reported to be developed for the quantification of beneficial biofertilizers utilized to maintain plant health and growth. Similarly, Guo et al. developed a portable extended-gate field-effect transistor (EG-FET) sensing system integrating a screen-printed gold extended-gate electrode functionalized with monoclonal antibodies for the specific detection of enterohemorrhagic *E. coli* O157:H7 in buffered food samples. The device exhibited a linear calibration range of 10^4–10^{10} CFU/mL and demonstrated strong specificity, with a maximum interference response of only 13% relative to the target signal when evaluated against common foodborne pathogens, including *S. aureus*, *S. typhimurium*, and *L. monocytogenes* ($p < 0.001$) (Figure 6) [75].

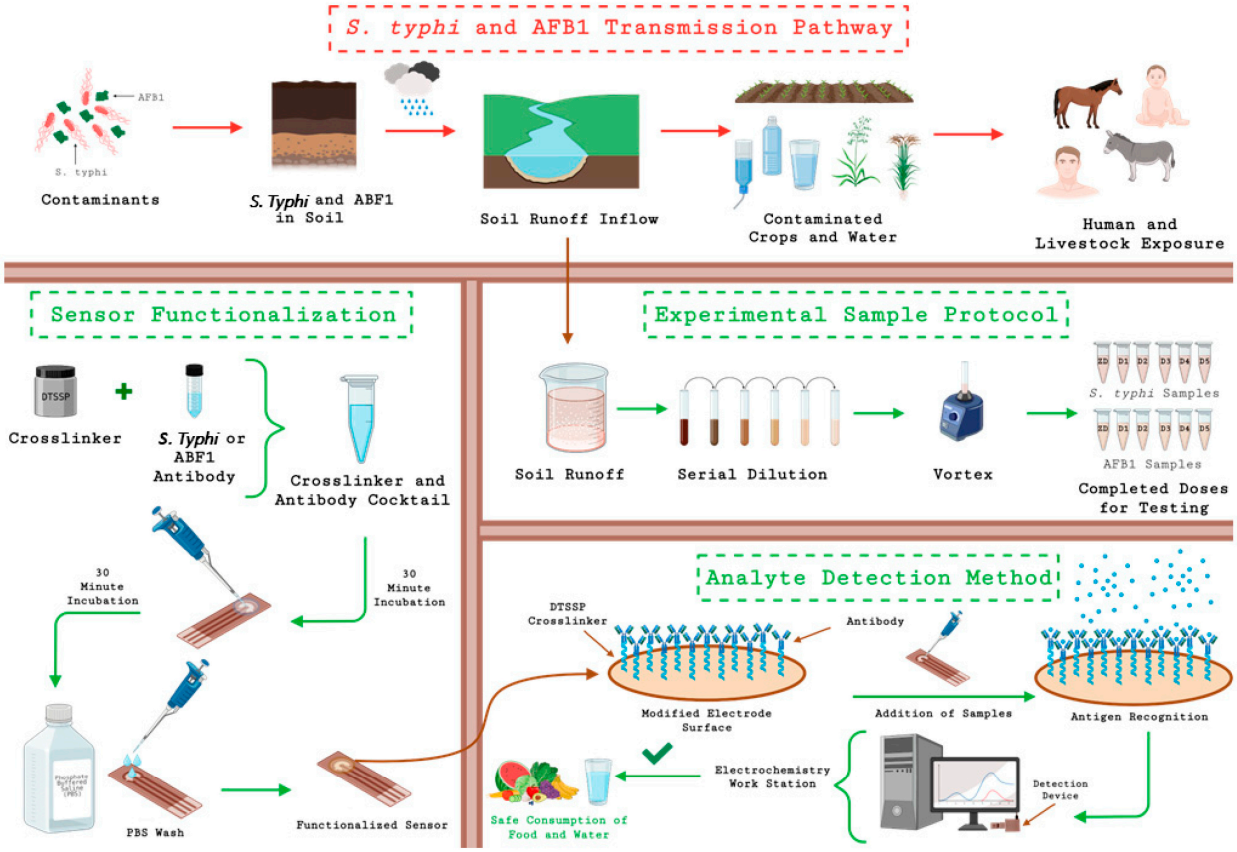

Figure 5. Schematic representation of the sample matrix preparation and electrochemical sensing workflow [73]. Reprinted from Ref. [73] (Biosensors, MDPI) © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY).

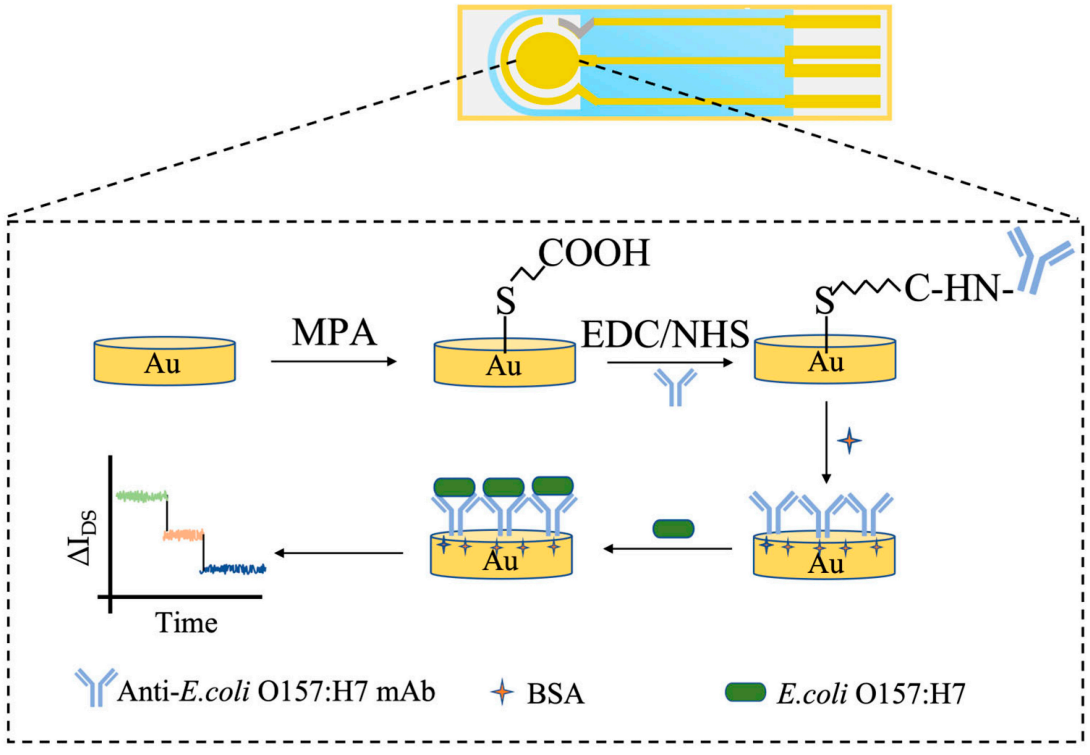

Figure 6. *Cont.*

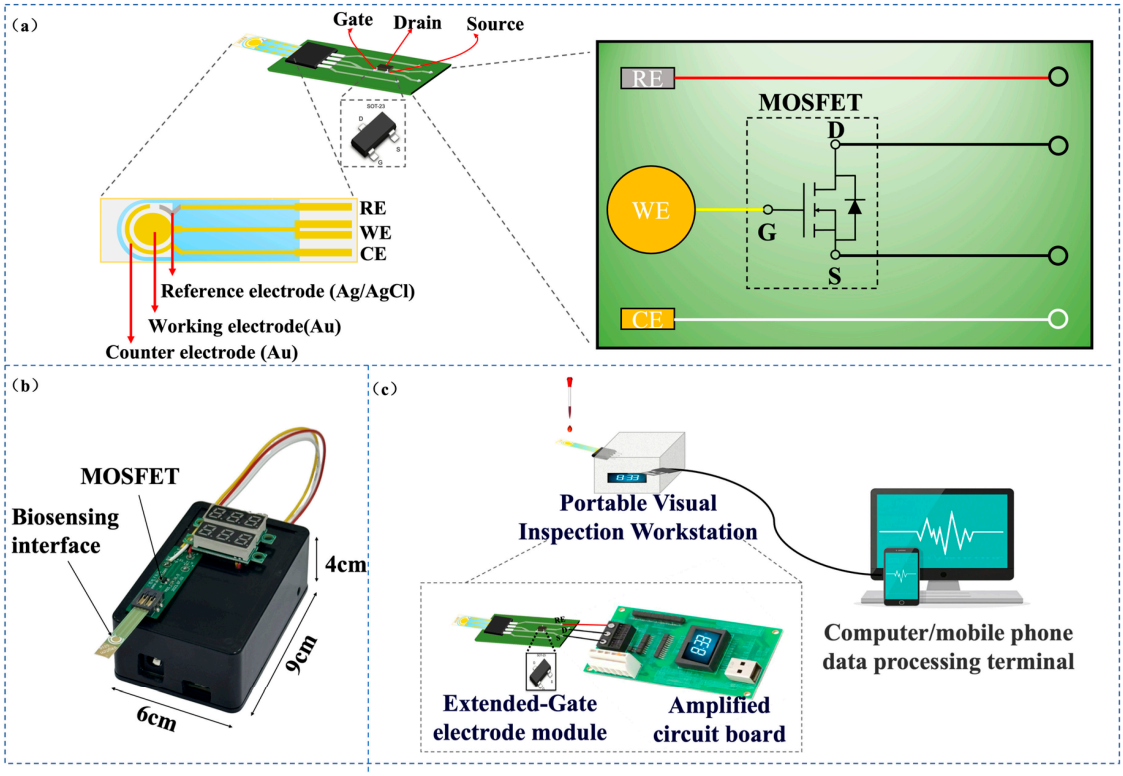

Figure 6. (**Top**): Schematic of the Antibody Immobilization Principle Based on the MPA Method. (**Bottom**): (**a**) Schematic of the extended-gate electrode module. The red signal line is connected to the reference electrode, the yellow signal line extends the gate of the MOSFET to the working electrode (a screen-printed Au electrode), and the black signal line connects the source and drain terminals of the MOSFET to the amplification circuit for current signal amplification. The counter electrode functions as a backup electrode. (**b**) Photograph and dimensions of the fabricated device. (**c**) Schematic diagram illustrating the overall system architecture [75]. Reprinted from Ref. [75] (Micromachines, MDPI) © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

3.3. Water and Environmental Monitoring

Waterborne bacterial contamination, propagated by various bacterial species, including *E. coli*, *Salmonella* spp., *Shigella* spp., *Y. enterocolitica*, *Campylobacter* spp., *Vibrio cholerae*, other *Vibrio* spp. (e.g., *V. parahaemolyticus*), *P. aeruginosa*, *L. pneumophila*, and *Mycobacterium* spp., remains a major concern for drinking water safety, wastewater treatment, and aquatic ecosystems [76–78]. Electrochemical sensors offer rapid and on-site detection of pathogenic bacteria such as *E. coli*, *V. cholerae*, and *L. pneumophila*. Recent innovations include self-cleaning electrodes, autonomous sensing platforms, and long-term deployment systems capable of operating in harsh aquatic environments. The use of nanostructured electrodes and bio-inspired recognition elements has significantly improved detection sensitivity and resistance to biofouling. Kumar Mishra et al. reported a portable, dual-plex, non-Faradaic electrochemical sensing platform for the rapid, specific detection of *S. typhimurium* and *E. coli O157* in potable water, achieving a turnaround time of 5 min. The system demonstrated LODs of 0.8 CFU/mL and 0.9 CFU/mL, respectively, within a concentration range of 10^1–10^5 CFU/mL. Detection specificity was achieved through antibody–antigen recognition targeting these pathogenic serotypes, with cross-reactivity evaluated between *S. typhimurium* and *E. coli*. However, broader strain-level validation or differentiation between pathogenic and non-pathogenic variants within the same species was not extensively reported [79] (Figure 7).

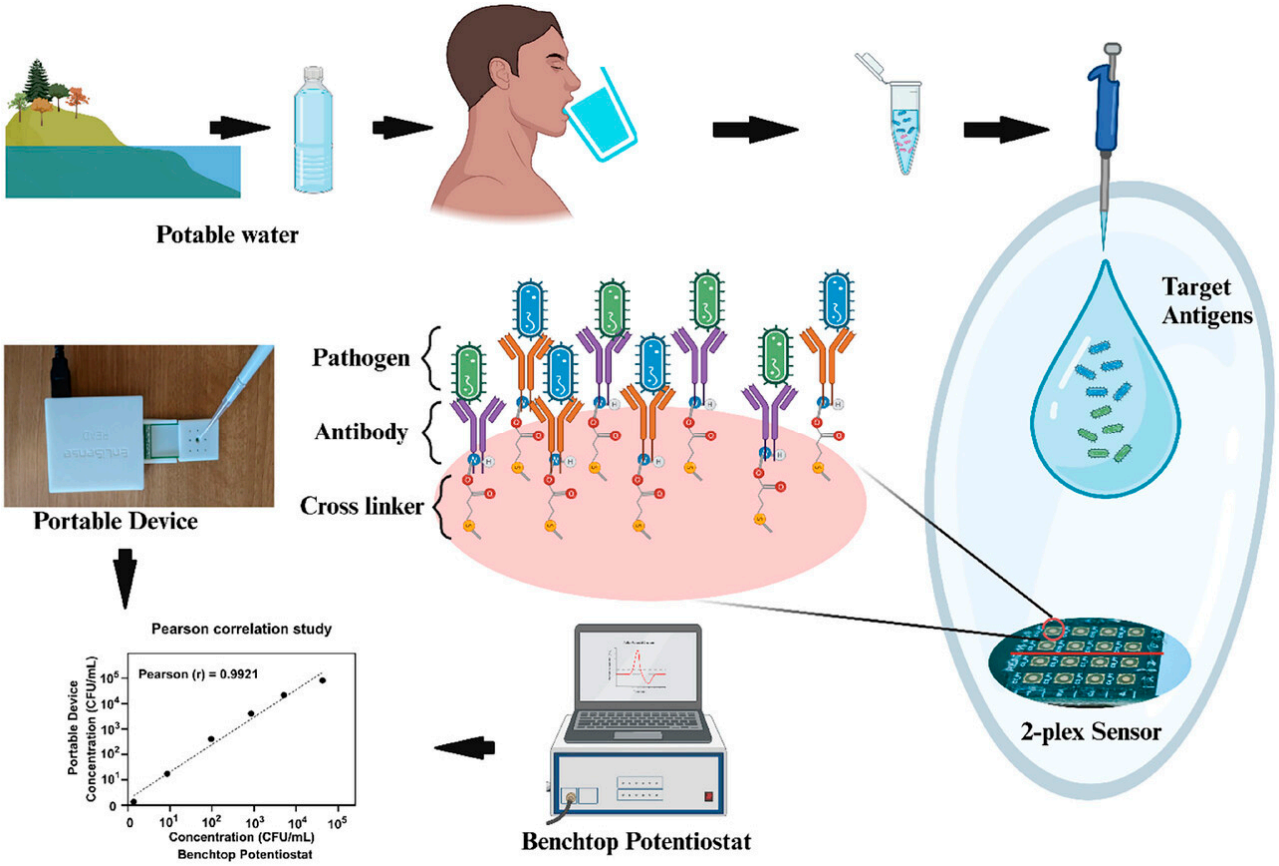

Figure 7. Schematic of the electrochemical detection of Salmonella and *E. coli* O157 on two plex sensor platforms [79]. Reprinted from Ref. [79] (Nano Select, Wiley), © 2025 The Author(s), Wiley-VCH GmbH. This is an open access article distributed under the terms of the Creative Commons CC BY license, which permits unrestricted use, distribution, and reproduction in any medium.

Osman et al. reported the specific electrochemical detection of *L. pneumophila* in cooling tower water samples with a microfluidic system that employed RNA-cleaving DNAzymes (RCDs) coupled with microgel magnetic beads programmed to release an electroactive DNA barcode. The LODs in buffer and cooling tower water samples were reported to be 1.4×10^3 CFU/mL and 1.9×10^3 CFU/mL, respectively [80]. Despite the slightly higher reported LODs compared to other antibody- or aptamer-based electrochemical biosensors, the strategy demonstrates promise in terms of reagent stability, cost-effectiveness, and potential suitability for integration into portable microfluidic platforms. A ratiometric DNAzyme electrochemical sensor was reported by Zhu et al. by combining electrochemical signals of a DNAzyme and MOFs and was analyzed via alternating current voltammetry (ACV) for the specific detection of *S. typhimurium* in urban water samples with an LOD of 1×10^5 CFU/mL [81]. Although the sensitivity is moderate compared to amplification-based biosensors, DNAzyme-based systems remain promising due to their chemical robustness, programmability, and potential for further signal amplification and on-site deployment.

Gunasekaran et al. reported an electrochemical sensor with bi-functional magnetic nanoparticle (MNP) (IgG antibody and ferrocene) conjugates for specific *E. coli* detection in water sources. With SWV, *E. coli* concentrations were reported to be in the range of 10^1–10^7 cells/mL in a dose-dependent manner [82]. Akhtarian et al. reported the integration of cell-imprinted polymers-functionalized stainless steel microwires (CIP-MWs) into a microfluidic device for the specific impedimetric detection of *E. coli* in water [83]. The LODs and quantification were determined to be 2×10^2 CFU/mL and 1.4×10^4 CFU/mL respectively with a dynamic range of 10^2 to 10^7 CFU/mL [83]. Ganesan et al. described a

label-free IgY-based electrochemical immunosensor for *E. coli* detection in water samples by employing boron- and nitrogen-doped Graphene Quantum Dots (B, N-doped GQDs) that specifically detected various concentrations of *E. coli*, with a linear working range of 0.5×10^1 to 10^7 CFU/mL and an LOD of 1.69 CFU/mL [84]. Real-time electrochemical water monitoring systems provide early warning signals for contamination events, supporting proactive water management and public health protection.

Beyond water systems, electrochemical sensors play a critical role in environmental monitoring of bacterial contamination. They are involved in the detection of different bacterial species, including *E. coli*, *Salmonella* spp., *L. pneumophila*, *Vibrio* spp., *Staphylococcus* spp., *Mycobacterium* spp., *Coxiella burnetiid*, *Streptococcus* spp., *and Clostridium* spp. These sensors enable the assessment of microbial risks associated with waste disposal, bioremediation processes, and climate-driven ecological changes. Park et al. reported a label-free, paper-based electrochemical peptide sensor for the specific economical quantification of airborne *B.subtilis* spores (as they are widely used non-pathogenic *B.anthracis* simulant spores) and an LOD of 6.9×10^2 CFU/mL in 30 min was reported, which they highlighted as showing potential for use in on-site airborne spore-monitoring systems [85]. Morawska et al. also reported a new electrochemical sensor for the specific detection and quantification of *B. anthracis* spores, based on thiol-modified electrodes. The detection limit was reported to be 10^3 CFU/mL with a sensitivity of 11 mV/log (CFU/mL). Due to the low unit cost, portability, and minimal apparatus demand noted by the authors, this method was reported to have the potential to be easily implemented in field analyzers for *B. anthracis* (Figure 8) [86].

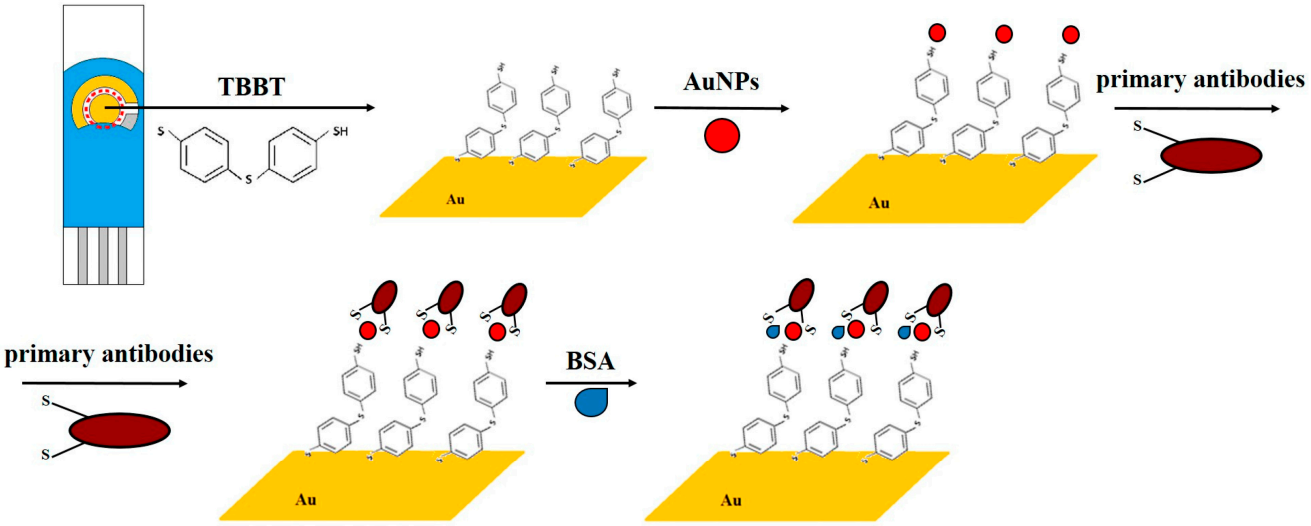

Figure 8. Modification of gold electrode: schematic illustration of the stages of modification. Cleaning of the gold electrode surface, formation of a self-assembled monolayer using 4-tert-butylbenzenethiol, deposition of gold nanoparticles, covalent immobilization of primary monoclonal antibodies specific to *Bacillus anthracis*, and passivation with bovine serum albumin to prevent nonspecific adsorption [86]. Reprinted from Ref. [86] (Sensors, MDPI) © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Environmental electrochemical sensors are increasingly designed with the aim of achieving durability, scalability, and autonomous operation. Although numerous studies have shown the successful application of these methods for the detection of bacterial pathogens in real water samples and the environment, the majority of these methods are still in the prototype or laboratory-validation stage. Hence, the real challenge is not the lack of real-world testing, but the transition of these methods from the prototype

stage or laboratory-validation stage to the level of commercially viable and regulatory-validated methods. The advanced electrochemical sensors and their modification features and performance are summarized in Table 2.

Table 2. Recent electrochemical sensors for bacterial detection with key features and response parameters.

Electrochemical Sensor	Detection Technique	Receptor	Bacteria Tested	Sample Type	Detection Response	Ref.
Health and Diagnostics						
Flexible electrochemical sensor with screen-printed Ag/AgCl interdigitated electrodes (IDEs)	Impedance-based sensor	Ag/AgCl-IDE electrodes	*E. coli*	Wound exudates	LOD: 10^2 CFU/mL Linear range: 10^2–10^7 CFU/mL	[55]
GCE-L-rGO electrochemical sensor	Voltammetric-based sensing	Liposomes	*E. coli* DH5α	*In vitro* testing	Detection sensitivity: ~26 µA. Cell densities: 3×10^3–3×10^4 cells/mL	[56]
NanoMIPs-based electrochemical sensor	Impedance-based sensor	Whole-cell molecularly imprinted polymer nanobody (nanoMIP)	*S. epidermidis*	*In vitro* testing	LOD: 1 CFU/mL Linear range: 10^1–10^6 CFU/mL	[57]
Cell-imprinted electrochemical impedance sensor	Impedance-based sensor	Whole-cell imprinted polymer	*E. coli*, *S. aureus*, and *Vibrio parahaemolyticus*	*In vitro* testing	Quantitative detection in the concentration range of 1.0×10^1~1.0×10^6 CFU/mL	[58]
MXene-AgNPs-SPCE label-free sensor	Impedance-based sensor	Bacteriophage receptor-binding protein-like peptide (BRBP)	*S. aureus*	Human serum and urine samples	Linear detection range: 10–10^6 CFU/mL LOD: 2.78 CFU/mL	[59]
$Ti_3C_2T_x$-PB/Chit/Au NPs modified dual-channel electrochemical aptasensor	Voltammetric aptasensor	Aptamer-based bioreceptors specific to C-reactive protein (CRP) and interleukin-6 (IL-6)	*E. coli* and Group B Streptococcus (GBS)	CRP and IL-6 plasma samples	Linear range CRP: 0.1–15 µg/mL IL-6: 0.01–100 ng/mL LODs: CRP: 0.075 µg/mL IL-6: 7 pg/mL	[60]
Wireless electrochemical biosensor	Impedance-based sensor	Antibiotic-coated (PD-Colis- and PD-Vanco) polymer dots	Carbapenem-resistant *K. pneumoniae* (CRKP) and MRSA	Human sputum samples	LODs: CRKP: 3.0 CFU/mL MRSA: 3.1 CFU/mL	[61]
MWCNTs/MXene/PVA composite hydrogel modified electrochemical sensor	Voltammetric-based sensing	MWCNTs/MXene/PVA composite hydrogel	PCN, UA, and HA (*P. aeruginosa* biomarkers) detection	Wound exudates	Detection limit range: 0.84~0.98 µM	[62]
Food Safety and Agriculture						
FeCoCuNiO-g-C_3N_4 based electrochemical aptasensor	Impedance-based sensing	DNA-based aptamer sensing	*P. aeruginosa*	Food samples	Detection limit: 3.03 CFU/mL	[65]
eGaIn based electrochemical sensor	Bioelectrochemical detection with ML-based signal interpretation	Whole-cell hydrogel platform	*E. coli*	Food samples	Linear range: 10^2–10^9 CFU/mL	[66]
NIP-Ppy-SPCE-Pt Electrochemical sensor	Pulsed amperometric detection	Whole-cell imprinted polypyrrole (MIP-Ppy) layer	*L. monocytogenes*	*In vitro* testing	LOD: 70 CFU/mL LOQ: 210 CFU/mL Linear range: 300–6700 CFU/mL	[67]
CNT-SPE electrochemical sensor	Enzyme-amplified electrochemical biosensing	Bacteriophage (T7)	*E. coli*	Leafy vegetable samples	Concentration range of 1–10^4 CFU/mL	[68]

Table 2. *Cont.*

Electrochemical Sensor	Detection Technique	Receptor	Bacteria Tested	Sample Type	Detection Response	Ref.
Food Safety and Agriculture						
PCR and CRISPR/Cas12a electrochemical sensor	Voltammetric and amperometric sensing	CRISPR/Cas12a-hairpin DNA probe interaction	*S. typhimurium*	Spiked poultry meat samples	Linear range: 6.7×10^1–6.7×10^5 CFU/mL LOD: 55 CFU/mL	[69]
BIF and Au@Fc-Apt sandwich electrochemical sensor	Sandwich electrochemical sensing	Whole-cell imprinted polymer film and aptamers	*S. aureus*	Milk samples	LODs: 10 CFU/mL	[70]
ZnO/Au-based, label-free electrochemical sensor	Non-Faradaic EIS-based sensing	Monoclonal antibody	*S. typhimurium*	Food samples	Detection limit: 9 CFU/mL	[71]
Portable, label-free electrochemical platform	Non-Faradaic EIS-based sensing	Antibody-based sensing	*S. typhimurium*	Spiked soil run-off samples	LODs: 1 CFU/mL Linear range 10–10^5 CFU/mL.	[73]
PGE-rGO-AuNPs modified electrochemical sensor	Voltammetric sensing	DNA-based sensing	*A. tumefaciens* T-DNA detection	*In vitro* testing	Linear range: 1.0×10^{-13}–1.0×10^{-9} M LOD: 0.87×10^{-13} M	[74]
Portable EG-FET-Au-SPE electrochemical sensor	Potentiometric electrochemical detection	Antibody-based sensing	Enterohemorrhagic *E. coli* O157:H7 (in presence of *S. aureus*, *S. typhimurium*, and *L. monocytogenes*)	Buffered food samples	Linear calibration range of 10^4–10^{10} CFU/mL	[75]
Water and Environmental Monitoring						
Portable two-plex electrochemical sensing platform	Non-Faradaic EIS-based sensing	Antibody-based sensing	*S. typhimurium* and *E. coli O157*	Potable water samples	LODs: 0.8 CFU/mL (ST) 0.9 CFU/mL (EC) Concentration range: 10^1–10^5 CFU/mL	[79]
Microfluidic electrochemical system coupled with microgel magnetic beads	Voltammetric and amperometric sensing	RNA-cleaving DNAzymes (RCDs)	*L. pneumophila*	Cooling tower water samples	LOD in buffer: 1.4×10^3 CFU/mL LOD in cooling tower water samples: 1.9×10^3 CFU/mL	[80]
Ratiometric DNAzyme-MOFs modified electrochemical sensor	Voltammetric sensing	DNAzyme-based sensing	*S. typhimurium*	Urban water samples	LOD: 1×10^5 CFU/mL	[81]
MNP-IgG-ferrocene modified electrochemical sensor	Voltammetric sensing	Antibody-based sensing	*E. coli*	Water samples	Concentration range: 10^1–10^7 cells/mL	[82]
CIP-MWs modified microfluidic electrochemical sensor device	Impedance-based sensing	Whole-cell imprinted polymers	*E. coli*	Water samples	LODs: 2×10^2 CFU/mL LOQs: 1.4×10^4 CFU/mL Dynamic range: 10^2–10^7 CFU/mL	[83]
Label-free B, N-doped GQDs based electrochemical sensor	Voltammetric and amperometric sensing	Antibody-based sensing	*E. coli*	Water samples	Sensitivity: 0.0395 µA. and 0.0491 µA. LODs: 0.5×10^1–10^7 CFU/mL	[84]
Label-free, paper-based electrochemical sensor	Voltammetric sensing	Peptide-based sensing	*B. subtilis*	Airborne spore samples	LOD: 6.9×10^2 CFU/mL	[85]
Electrochemical sensor with thiol modified gold electrodes	Voltammetric sensing	Antibody-based sensing	*B. anthracis*	Airborne spore samples	Detection limit: 10^3 CFU/mL sensitivity: 11 mV/log (CFU/mL)	[86]

The electrochemical sensors discussed in Table 2 have been grouped by an application-based structure because sensors are typically optimized and benchmarked within specific matrices (e.g., blood, food, and water, etc.). Sensor performance is strongly influenced by matrix-dependent factors such as biofouling, ionic strength, background microbiota,

matrix effects, sample pretreatment requirements, and required detection limits. Grouping sensors by application, therefore, allows for a clearer view of the practical challenges and translational considerations unique/specific to each field rather than any limitations associated with the sensors themselves. Most of these sensors have only been subjected to preliminary testing/studies with the potential for validation highlighted, and their associated electrochemical transduction principles have been demonstrated to be versatile in different application environments. Notably, the domain in which these sensors could be applied is largely dependent on the biorecognition elements used in them and the associated sample preparation protocols.

In some instances, validation was carried out using a single bacterial species. However, testing using a single species (i.e., *E.coli*), although common, does not automatically qualify the sensor as having exclusive specificity. Therefore, the bacterial species listed can be regarded as having been used for testing, not exclusivity. Although the electrochemical sensors listed hold immense promise for use in different sectors, having the potential for cross-sector use, various factors such as the receptor used, the surface, and the matrix optimization can ensure that the sensors can be applied to different uses, provided that the specificity and selectivity of the sensors are assessed.

4. Persistent Challenges and Future Directions

4.1. Implementation Issues

These remarkable advances in electrochemical sensor technologies for bacterial detection notwithstanding, limited large-scale field deployment, regulatory validation, and commercialization beyond proof-of-concept stages have been key hurdles to development. Therefore, these advancements have often been relegated to mere prototypes, effective only in laboratories. The lack of translation measures for next-generation electrochemical sensors can turn their innate sensitivity into an additional hurdle to overcome, as their overall performance can be affected by fluctuations in factors including temperature, pH, ionic strength, and redox-active interferents, which are always present in biological, food, and environmental samples. Over time, exposure to these unstable conditions may result in baseline shift, signal loss, and diminished accuracy, and thus these sensors can lose their effectiveness for long-term monitoring. Additionally, electrode fouling can occur, which can prove to be constraining, particularly for testing complex real-world sample matrices like blood, wastewater, food homogenates, or soil extracts. Proteins, lipids, polysaccharides, and other organic molecules in the sample get adsorbed nonspecifically on the electrode surfaces, thus blocking the active sites, modifying electron-transfer kinetics, and drastically decreasing sensor response [87–89]. Although some advancements in the areas of antifouling surface coatings, nanostructured materials, and bio-inspired interfaces have given good results, it is currently proving to be very difficult to obtain a long-term resistance to fouling without losing significant sensor sensitivity [90,91].

Moreover, issues with reproducibility of results and standardization hinder the active commercialization of this technology. Modifications of high-end electrochemical sensor systems currently developed with sophisticated nanomaterials, multi-step surface functionalization, or biological recognition elements like enzymes, antibodies, or aptamers, aid in increasing the target detection limit and specificity [92]. However, different batches of materials, changes in surface chemistry, and variations in the immobilization processes can cause variability in the sensor performance, hence making it difficult to achieve batch-to-batch reproducibility, which makes quality control and large-scale production complicated [93]. Additionally, a lack of standardized regulatory measures and benchmarking protocols for sensor performance evaluation such as detection limits, selectivity, stability, reproducibility, and lifespan to determine effective cross-platform comparison and regulatory assessment

severely restricts developmental activities [94,95]. From the viewpoint of regulatory and implementation aspects, the clinical and industrial use of these sensors for active and continuous bacterial detection is made more complicated by the requirement of approvals, especially in the healthcare and food safety sectors. For long-term reliability, robustness, and meeting regulatory criteria, thorough validation studies are required, which can be quite demanding. Furthermore, the requirement of rigorous training for potential regular users, regulated calibration, and data interpretation skills can be an additional obstacle for adoption in low-resource or decentralized settings, where rapid and user-friendly diagnostic tools are desperately required [96,97].

4.2. Emerging Opportunities

To counter these hurdles, novel research avenues, innovations, and modifications to preexisting technologies provide alternative routes to break through existing limitations and restructure the overall potential of these electrochemical bacterial sensors. Importantly, these emerging strategies must be viewed as targeted solutions to the implementation bottlenecks discussed in Section 4.1, including sensor fouling, signal drift, limited long-term stability, poor reproducibility, and a lack of regulatory standardization. Hence, the key targets of future studies should be the design and development of more durable and self-sufficient sensor platforms. Self-cleaning electrodes, adaptive signal correction, and real-time self-calibration are some of the ideas being explored to combat fouling, drift, and environmental variation [98,99]. Such approaches directly respond to baseline shifts, signal degradation, and environmental susceptibility by enabling autonomous compensation for fluctuations in temperature, pH, ionic strength, and redox-active interferents that commonly affect real-world sample analysis. Additionally, the use of reusable and regenerable sensing surfaces can lead to a major drop in operational costs and also marginally improve and support sustainability initiatives. Regenerable interfaces further mitigate electrode fouling caused by nonspecific adsorption of biomolecules in complex matrices such as blood, wastewater, and food extracts, thereby improving operational lifespan and reliability.

At the crossroads of electrochemical sensing, synthetic biology, and advanced nanomaterials, there is a promising path to explore. Genetically modified cells or synthetic receptors, for example, can be engineered to detect specific bacterial metabolites or virulence factors selectively, thereby providing unprecedented specificity [100,101]. By enhancing molecular-level recognition fidelity, these engineered systems can also reduce cross-reactivity and batch-to-batch variability associated with conventional biorecognition elements, thereby improving reproducibility and facilitating quality control during scale-up. Nanomaterial breakthroughs, like 2D materials, MOFs, and hybrid nanocomposites, are simultaneously transforming the functional terrain of sensor electrodes by facilitating electron transfer, amplifying surface area, and allowing for multi-analyte detection [102,103]. In addition to sensitivity enhancement, rationally designed nanomaterials with controlled surface chemistry can contribute to improved fabrication consistency and standardized performance metrics, addressing commercialization barriers linked to material heterogeneity. Wearable and flexible electrochemical sensors, which are gaining ground, also extend the horizon of bacterial monitoring. The use of textiles, skin-mounted platforms, or implantable devices means continuous, non-invasive or minimally invasive monitoring in healthcare, occupational safety, and environmental exposure is achievable. Through wireless communication and Internet of Things (IoT) advancements, such a setup would be able to both send real-time data and enable large-scale monitoring of different environments [104–106]. When coupled with robust validation frameworks and standardized calibration protocols, these platforms could accelerate regulatory acceptance and real-world deployment, particularly in decentralized and resource-limited settings where user-friendly operation is essential.

The integration of artificial intelligence (AI) and machine learning (ML) is expected to have the potential to radically transform electrochemical sensors for bacterial detection by making them more powerful, versatile, and faster in their analytics [107]. Beyond analytical enhancement, AI-driven frameworks directly address challenges of signal variability, environmental interference, and operator-dependent interpretation highlighted in Section 4.1. Latest studies show that with AI-based signal processing, sensor precision and sensitivity can be significantly improved even in complex samples; thus, multilayer perceptrons, random forests, and neural networks processing multidimensional electrochemical data can accurately categorize or quantify pathogenic bacteria like *E. coli* in an extensive concentration range with very high accuracy and reduced detection time compared to conventional culture methods [58,108,109]. Sophisticated data-centric algorithms can identify almost invisible characteristics in highly complicated electrochemical signals so that bacterial species and strain discrimination can be more accurate. Moreover, AI-powered signal processing can also offset the effects of noise, drift, and the matrix, thus making the sensor more reliable under real-world conditions [110]. Such computational compensation strategies enhance reproducibility across sensor batches and operational environments, thereby supporting regulatory benchmarking and cross-platform comparison.

Besides detection, ML-based predictive analytics can be utilized for early warning systems, trend analysis, and disease outbreak forecasting, especially when the sensors are in a networked or distributed arrangement. ML algorithms go far beyond simple pattern identification as they can help in the sensor development process optimization, including the selection of electrode materials or the adjustment of biorecognition elements (e.g., aptamers and antibodies), while deep learning methods are expected to deliver even better noise reduction, feature extraction, and multiplexed detection in real samples, e.g., food, water, and clinical specimens [111–113]. Importantly, AI-assisted optimization can streamline sensor fabrication workflows, minimize variability during surface functionalization, and promote scalable manufacturing practices. With continuous research, the new generation of AI-based electrochemical devices is anticipated not only to deliver lower detection limits and rapid results but also to facilitate on-site decision-making, adaptive calibration, and automatic anomaly detection without the requirement of trained personnel. This reduction in user dependency directly addresses the training and expertise barriers that limit adoption in low-resource settings.

Concurrently, the integration of IoT technologies and Geographic Information System (GIS) with electrochemical bacterial sensors affords novel possibilities in spatio-temporal monitoring in the context of environmental and public health [114]. Integration of low-cost IoT sensors into various workflows facilitates real-time water quality and bacterial proxy data collection, which can then be sent to cloud platforms for overall analysis and trend prediction with automated alert integration. This ensures a smooth transition from alerting to prevention in surveillance [115]. Standardized cloud-based data architectures and centralized analytics can further support harmonized performance evaluation, facilitating regulatory compliance and large-scale quality assurance. When GIS is additionally integrated, these streams of data can be geo-visualized to produce contamination hotspot maps, monitoring the spread of microbial pollution, and linking bacterial signals with environmental factors such as hydrology, land use, or demographic risk profiles, leading to better outbreak prediction and resource allocation in a geographic context [116]. In the future, the combination of AI, ML, IoT, and GIS will not only result in more intelligent biosensing gadgets but also in thorough, interconnected systems that associate molecular-level bacterial detection with spatial analytics and real-time decision-making, thus revolutionizing the ways in which we monitor water and environmental safety, manage public health responses, and comprehend microbial dynamics on a large scale [117]. Such interconnected

ecosystems may also facilitate longitudinal validation studies and post-market surveillance, which are essential for sustained regulatory approval and commercialization.

Ultimately, the steadily increasing focus on sustainability and green engineering offers a revolutionary chance for the effective development of electrochemical sensing technologies. If these localized sensors are scaled further for use in POC settings, mainly in environmental, agricultural, and resource-limited settings, the ensuing environmental footprint will be a top design consideration [118]. Addressing sustainability simultaneously responds to commercialization barriers, as cost-effective and environmentally responsible designs improve public acceptance, regulatory alignment, and long-term deployment feasibility. Using biodegradable or bio-derived substrates such as cellulose-based papers, silk fibroin, chitosan, polylactic acid, or other compostable polymers can greatly lower the waste generated from single-use or short-life sensors to facilitate environmentally safe disposal. A simultaneous switch to electrode materials that are abundant on Earth, recyclable, or carbon-based (e.g., graphene, biochar, carbon inks, or metal-free catalysts), in place of scarce or toxic materials, will not only help sensor fabrication to be in line with circular economy principles but also maintain consistent sensor performance [119,120]. Material standardization using earth-abundant and well-characterized substrates may additionally improve batch consistency and reduce variability in large-scale manufacturing. These breakthroughs serve not only to facilitate sustainability but also to produce flexible, lightweight, and low-cost devices that facilitate mass manufacturing and are ideal for decentralized sensing. The significance of switching to low-energy, eco-friendly manufacturing processes that produce minimal chemical waste and carbon emissions cannot be overlooked.

Manufacturing technologies like screen printing, inkjet printing, and roll-to-roll processing open the way to the mass production of sensors at room temperature, which cuts down energy usage when compared to traditional microfabrication [121,122]. Such scalable fabrication strategies can significantly enhance reproducibility, simplify quality control, and bridge the gap between laboratory prototypes and commercially viable products. Green routes for synthesizing nanomaterials, such as using plant-based reducing agents or microbial synthesis, raise the sustainability level of electrochemical biosensors even more. This set of measures is especially effective if sensors are to be used in environmental and agricultural monitoring on a large scale, where thousands of single-use sensors are spread over fields, waterways, or networks of public utilities. Here, sensors in environmentally friendly packaging help to avoid secondary contamination, facilitate adherence to regulations, and win the approval of the general public [123]. Embedding sustainability metrics as well as sensitivity, selectivity, and cost into sensor design frameworks will be necessary to guarantee that forthcoming electrochemical sensing technologies are not only analytically high-performing but also socially and environmentally responsible, thereby ensuring a mutually beneficial scenario for all stakeholders involved.

5. Conclusions

Electrochemical sensors have emerged as one of the most important and growing technologies in the detection, recognition, and real-time tracking of bacterial pathogens in important areas such as health diagnostics, food safety, smart agriculture, water quality evaluation, and environmental monitoring. The advantages of electrochemical sensors, such as high sensitivity, speed, low-power consumption, scalability, and compatibility with portable systems, have made them an innovative solution in the modern world of pathogen detection and monitoring. Recent developments in the materials used in the electrodes, such as nanostructured metals, carbon-based nanomaterials, and conductive polymer-based materials, have improved the analytical performance of the sensors by

optimizing the electron transfer rate and the effective surface area of the materials, resulting in highly selective and low-limit detection of bacterial pathogens.

While these achievements represent tremendous progress, the translation of electrochemical bacterial sensors from the laboratory bench to the commercial marketplace represents the major hurdle. Some of the challenges that need to be overcome include stability, batch-to-batch reproducibility, manufacturability, and performance in complex matrices. Challenges such as biofouling, stability, and matrix effects continue to affect the reliability of the analytical performance of the sensors, particularly with clinical or environmental matrices. Another set of challenges that need to be overcome includes standardization, validation, and cost-effectiveness, etc.

In the future, the progress of electrochemical bacterial sensors will not be based on improvements made to the sensitivity of the sensors but will be based on the overall performance of the systems. Moreover, the electrochemical bacterial sensors will be smart, automated, multiplexed, and capable of providing reliable real-time data. It is expected that with continued efforts made toward the durability, standardization, and manufacturability of the electrochemical bacterial sensors, the future of electrochemical bacterial sensors will be pivotal to the advancement of efficient diagnostics and the protection and sustenance of global health and environmental safety.

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Abbreviations

The following abbreviations are used in this manuscript:

AFM	Atomic force microscopy
AI	Artificial intelligence
AMR	Antimicrobial resistance
BIF	Bacteria imprinted polymer film
CFU	Colony-forming unit
CRKP	Carbapenem resistant *K. pneumoniae*
CV	Cyclic voltammetry
DLS	Dynamic light scattering
DPV	Differential pulse voltammetry
EIS	Electrochemical impedance spectroscopy
ELISA	Enzyme-linked immunosorbent assay
GIS	Geographical information systems
IoT	Internet of things
LOD	Limit of detection
LOQ	Limit of quantification
LSV	Linear sweep voltammetry
ML	Machine learning

MNP	Magnetic nanoparticle
MOFS	Metal–organic frameworks
MRSA	Methicillin resistant *S. aureus*
PAD	Pulsed amperometric detection
PCR	Polymerase chain reaction
PEC	Photoelectrochemical biosensors
POC	Point-of-care
PPV	Positive predictive value
SWV	Square-wave voltammetry
TEM	Transmission electron microscopy

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