Editors' Choice—Review—Advances in Electrochemical Sensors: Improving Food Safety, Quality, and Traceability

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Editors' Choice—Review—Advances in Electrochemical Sensors: Improving Food Safety, Quality, and Traceability

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Electrochemical sensors have become a pivotal tool in ensuring the safety and security of the global food supply chain, which is crucial for public health, economic stability, and environmental sustainability. Modern food systems, with their complex global distribution and varied processing methods, require advanced solutions for detecting contaminants and maintaining food quality. This review delves into recent advancements in electrochemical food sensor technology, highlighting their operating principles, types, cutting-edge materials, and methods enhancing their effectiveness. These sensors are adept at identifying a broad range of foodborne pathogens, chemical contaminants, and adulterants while monitoring food freshness and quality. Innovations include using nanomaterials and conductive polymers and shifting towards miniaturized, portable devices for on-site and real-time analysis. The review also addresses challenges such as sensitivity, selectivity, and matrix effects, pointing out emerging trends and future research avenues to overcome these hurdles. Regulatory and standardization issues relevant to adopting these technologies in food safety protocols are also considered. Highlighting the last three years, this review emphasizes the indispensable role of electrochemical sensors in boosting food safety and security and the need for ongoing innovation and cross-disciplinary cooperation to advance this area.

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The imperative for ensuring food safety and security is a global concern that resonates across public health, economics, and environmental sustainability. The assurance of safe and secure food supplies is fundamental to societal well-being, impacting not only individual health outcomes but also economic stability and international trade relations.[1,2] The challenges in maintaining food safety and security are multifaceted, encompassing the detection and control of microbial pathogens, chemical contaminants such as pesticides and heavy metals, and the prevention of food adulteration and fraud.[3,4] These issues are compounded by the complexities of a globalized food supply chain, where the provenance and handling of food products across diverse geographical and regulatory landscapes introduce additional vectors for contamination and quality degradation. The repercussions of lapses in food safety and security are severe, ranging from acute public health crises due to foodborne illnesses to long-term consequences on consumer trust and market dynamics.[5] In 2024, Sun et al. introduced a groundbreaking method for improving food safety through rapidly and precisely detecting the food contaminant Sudan Red I, combining electrochemical sensors with machine learning technologies. Their research utilized a modified stainless steel needle electrode enhanced with silver nanoparticles (AgNPs) and explored the application of three convolutional neural network architectures, Inception V1, ResNet-50, and SqueezeNet V1.1, to accurately predict sensor responses. The AgNPs/SSN electrode demonstrated increased electrochemical reactivity towards Sudan Red I, achieving a linear detection range from 0.1 to 20 μM and a remarkable detection limit of 10 nM.[6] Thus, developing and implementing effective, reliable, and rapid detection methods are crucial for monitoring the integrity of the food supply and for the proactive management of potential risks.

Within this context, electrochemical sensors have emerged as a highly promising class of analytical tools, offering unique advantages in terms of sensitivity, specificity, portability, and the capability for real-time analysis. Electrochemical sensing technology capitalizes on the principle that specific analytes within a sample can induce quantifiable changes in electrical properties, such as current, potential, or impedance. These changes directly measure the analyte's concentration, allowing for the precise detection and quantification of contaminants and quality indicators within food matrices. The adaptability of electrochemical sensors to a wide range of detection scenarios is facilitated by the diversity of sensing modalities—including amperometric, potentiometric, conductometric, and impedimetric sensors—each tailored to specific types of analytes and analytical requirements. Moreover, the recent advancements in sensor materials, including nanomaterials and conductive polymers, and sensor design, such as miniaturization and integration with microfluidic systems, have significantly extended the capabilities of electrochemical sensors. These innovations enable enhanced performance in complex food matrices, overcoming some traditional challenges associated with food sample analysis. For instance, Li et al. address the environmental and public health concerns of the widespread misuse of antibiotics and lean meat powder, emphasizing the need for rapid, onsite detection methods to mitigate potential risks. They introduce a novel approach using flexible graphene electrodes (FGE) crafted via CO_2 laser in ambient conditions, integrated with a portable electrochemical analyzer for electronic signal transmission. This innovative, laser-enabled flexible electrochemical sensor, designed for finger application, allows for the immediate onsite identification of chloramphenicol (CAP), clenbuterol (CLB), and ractopamine (RAC) in meat products. The sensor demonstrates sensitivity with detection limits for CAP, CLB, and RAC at 2.70, 1.29, and 7.81 μM, respectively, and showcases a practical application with minimum detection concentrations in natural pork and milk samples.[7]

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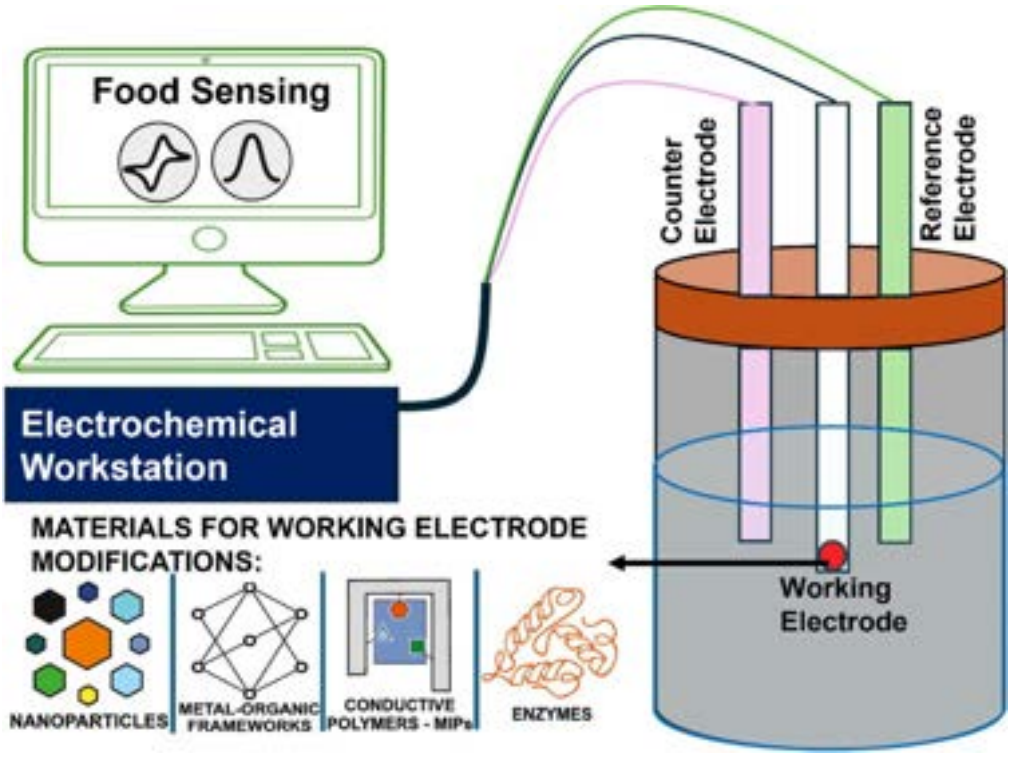

Scheme 1. Electrochemical sensing system.

Currently, the market for electrochemical sensors specifically designed for food safety applications is still evolving, with a limited number of technologies achieving widespread commercial success. One of the primary reasons for this is the complexity of food matrices, which can vary greatly and thus require sensors with high levels of specificity and sensitivity. Despite these challenges, there are promising developments. For example, sensors for detecting specific contaminants like pesticides, heavy metals, and pathogens are being refined and have started to find their way into the market.[8,9] These sensors typically utilize advanced materials such as nanocomposites and conductive polymers to enhance their performance. While the success and reliability of these sensors are not yet on par with medical counterparts such as glucose monitors, ongoing research and technological improvements are expected to increase their prevalence in real-world food safety applications in the near future.

This review aims to meticulously explore the recent advancements in electrochemical sensor technologies, particularly emphasizing their applications in ensuring food safety and security. By providing a detailed examination of the operational principles of electrochemical sensors, the review elucidates the mechanisms underlying their functionality and the technological innovations that have propelled their development forward. It delves into the various types of electrochemical sensors, discussing their advantages, limitations, and applicability to different analytical challenges in food safety. The review also highlights the cutting-edge materials and methodologies shaping the future of electrochemical sensing, from surface modification techniques to integrating sensors with advanced data processing and machine learning algorithms. In addressing the challenges and limitations of current sensor technologies, the review identifies critical areas for future research and development, emphasizing the need for improved sensitivity, selectivity, and stability, as well as the integration of sensors into comprehensive food safety management systems. Furthermore, the review considers the regulatory and standardization aspects critical to adopting and implementing electrochemical sensors in food safety practices. Through an exhaustive survey of literature from the past three years, this review aims to provide a foundational understanding of the state of the art in electrochemical sensor technology and its pivotal role in advancing food safety and security. In doing so, it underscores the importance of continued research and interdisciplinary collaboration in harnessing the full potential of these technologies to meet the complex challenges of ensuring safe, secure, and sustainable food systems worldwide.

Fundamentals of Electrochemical Sensors

Principles of electrochemical sensing.—As shown in Scheme 1, electrochemical sensors are sophisticated devices that control the interaction between chemical reactions and electrical signals to detect and quantify specific analytes in various samples, including those critical for ensuring food safety and security. At the heart of electrochemical sensing technology lies the conversion of a chemical signal generated by the interaction of an analyte with an electrode into an electrical signal that can be easily measured and interpreted. This process primarily hinges on the redox reactions that occur at the surface of the working electrode when it comes into contact with the target analyte, leading to a change in electrical current or potential that is directly proportional to the concentration of the analyte. The operational foundation of these sensors encompasses a working electrode where the analyte undergoes either oxidation or reduction, a reference electrode that serves as a stable point of reference for the working electrode's potential, and typically a counter electrode to facilitate the flow of electrons through the circuit by completing the electrical loop. This setup is immersed in an electrolyte solution to ensure the seamless movement of ions, which is essential for the redox reactions.[10,11]

Electrochemical detection methods are diverse, with amperometry, voltammetry, impedance spectroscopy, and potentiometry being the most widely used techniques. Amperometry involves measuring the current at a constant potential, which reflects the rate of the redox reaction and, thus, the concentration of the analyte. Voltammetry varies the potential at the working electrode and measures the resulting current, enabling the identification and

quantification of analytes based on their unique redox potentials. Impedance spectroscopy offers insights into the redox processes' kinetics and the electrode-electrolyte interface's electrical properties by analyzing the impedance across a range of frequencies. Potentiometry measures the potential difference between the working and reference electrodes without drawing significant current, which can be related to the ion concentration in the solution through the Nernst equation. The performance of electrochemical sensors, particularly their sensitivity and selectivity, is significantly enhanced by modifying the electrode surfaces with advanced materials such as nanoparticles, conducting polymers, and enzymes. These modifications aim to increase the effective surface area of the electrode, facilitate electron transfer, and introduce specific sites for the selective binding of target analytes. Such enhancements are crucial for detecting low concentrations of hazardous substances, including pathogens, toxins, pesticides, and heavy metals, which pose significant risks to food safety and security. Through these advancements, electrochemical sensors provide a powerful tool for the real-time, on-site monitoring of food products, offering rapid, accurate, and cost-effective alternatives to conventional laboratory-based analytical methods.[12]

Types of Electrochemical Sensors Relevant to Food Safety

Amperometric sensors.—Amperometric sensors are highly specialized electrochemical devices that quantify analyte concentrations by measuring current resulting from redox reactions at a constant applied potential. According to Faraday's laws of electrolysis, these sensors exploit the direct relationship between the current intensity and the analyte concentration. The electrochemical reaction is facilitated by applying a potential sufficient to drive the oxidation or reduction of the target analyte at the sensor's electrode surface. This capability makes amperometric sensors particularly adept at detecting trace levels of specific chemicals, such as pesticides, mycotoxins, and heavy metals in complex food matrices. The design of these sensors often incorporates advanced materials for electrode modification, such as carbon nanotubes or metal nanoparticles, to enhance surface area, electron transfer rates, and selectivity towards specific analytes, thereby improving the sensor's sensitivity and specificity for food safety applications.[13,14]

Potentiometric sensors.—Potentiometric sensors operate based on the measurement of the potential difference between a working electrode and a reference electrode, with this potential being directly related to the logarithm of the ion activity in the sample, as described by the Nernst equation. These sensors are particularly suited for the detection of ions and pH levels in food products, providing crucial information for assessing food quality and safety. Ion-selective electrodes, a category within potentiometric sensors, are designed with selective membrane materials that respond to specific ions, allowing for the targeted detection of contaminants such as nitrates or the monitoring of essential nutrients. The selectivity is achieved through membranes that incorporate ionophores or other selective binding agents, which provide the basis for the sensor's response to particular ionic species, making potentiometric sensors invaluable for ensuring compliance with food safety standards.[15]

Conductometric sensors.—Conductometric sensors measure the electrical conductivity of a solution, which changes in the presence of analytes due to the alteration in the ionic strength and mobility. These sensors are based on the principle that the conductance of an electrolytic solution is proportional to the concentration of ionic species, making them useful for applications such as monitoring fermentation processes, where the production or consumption of ions reflects microbial activity. The simplicity and versatility of conductometric sensors, combined with their ability to provide real-time measurements, make them suitable for a wide range of applications in food quality and safety monitoring, including the detection of adulteration and the assessment of product freshness.[16]

Impedimetric sensors.—Impedimetric sensors assess the impedance of an electrode-electrolyte interface, offering insights into the electrochemical properties and surface phenomena related to the presence of analytes, particularly microorganisms. These sensors analyze the complex impedance, which includes both resistance and reactance, at various frequencies to deduce information about the kinetics of electrochemical reactions, the double-layer capacitance, and changes in the physicochemical properties of the electrode surface due to microbial adhesion. This method is highly sensitive to the early stages of microbial growth, making impedimetric sensors a powerful tool for the rapid detection of bacterial contamination in food products. The development of impedimetric sensors for food safety is focused on enhancing the interface between the sensor and the complex food samples to improve the detection limits and selectivity for pathogenic microorganisms.[17,18]

Key Components and Operation of Electrochemical Sensors

Electrochemical sensors' key components and operation are central to their functionality and effectiveness in applications such as food safety. These sensors typically consist of three primary electrodes: the working electrode, the reference electrode, and the counter (or auxiliary) electrode, all of which play critical roles in the electrochemical detection. The operation of these sensors involves intricate electrochemical reactions and processes that enable the detection and quantification of analytes in various samples.

Working electrode.—The working electrode is the central component of an electrochemical sensor, where the redox reactions of the analyte of interest occur. The material and surface properties of the working electrode are crucial, as they directly affect the sensor's sensitivity, selectivity, and overall performance. Common materials for working electrodes include metals (such as gold and platinum), carbon (in forms such as graphite, carbon paste, or carbon nanotubes), and conductive polymers. The choice of material depends on the specific application and the nature of the analyte to be detected. Modifying the working electrode surface with catalysts, enzymes, or specific recognition elements can enhance the electrode's selectivity for the target analyte, improving the sensor's performance in complex matrices like food samples.[19,20]

Reference electrode.—The reference electrode provides a stable, known potential against which electrode working electrode's potential is measured. This stability is crucial for accurate and reproducible measurements. The reference electrode does not participate in the redox reactions but serves as a benchmark for potential measurement. Common reference electrodes are the silver/silver chloride (Ag/AgCl) and the saturated calomel electrode (SCE), chosen for their stable and well-defined electrode potentials.[19,20]

Counter electrode.—The counter (or auxiliary) electrode completes the electrical circuit by facilitating the flow of electrons in and out of the electrochemical cell. In doing so, it balances the current generated at the working electrode by undergoing complementary redox reactions. The counter electrode material is generally inert, with platinum being a common choice due to its wide potential window and chemical stability.[19,20]

Operation of electrochemical sensors.—An electrochemical sensor's operation begins with applying a potential or current between the working and reference electrodes. This induces a redox reaction at the surface of the working electrode involving the analyte. The nature of the response depends on the type of sensor and the detection method (e.g., amperometric, potentiometric, conductometric, impedimetric). The resulting electrical signal—be it current, potential change, or impedance variation—is directly related to the concentration or presence of the analyte and is measured by the sensor's electronics. The sensor's response is then processed and interpreted, often with calibration curves or

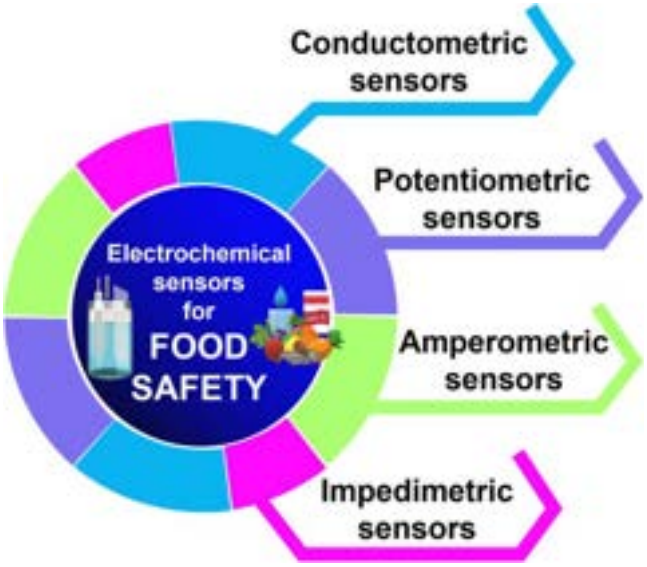

Figure 1. Major types of electrochemical sensors for food safety.

algorithms, to quantify the analyte's concentration. In food safety applications, this enables the detection of contaminants, pathogens, or nutrient levels, providing critical information for quality control and safety assessments.[19,20]

Applications of Electrochemical Sensors in Ensuring Food Safety and Security

Integrating electrochemical sensors into food safety and security protocols represents a significant advancement in detecting and quantifying contaminants that pose risks to public health. These devices influence the principles of electrochemistry to provide rapid, accurate, and sensitive analyses, which are essential for monitoring the safety of the food supply.[21–24] The scientific underpinnings of these sensors, combined with innovative material science and biochemistry, have led to the development of highly specific and efficient methods for detecting a range of hazardous substances, including pesticides, heavy metals, pathogens, and mycotoxins, as shown in Fig. 2.

Detection of contaminants.— *Pesticides.*—Kadu et al. emphasize the urgency of detecting agricultural and domestic pesticides, given their adverse effects on health and the environment. They advocate electrochemical sensors as a superior alternative to conventional detection methods due to their onsite applicability, cost-effectiveness, and high sensitivity. The research focuses on utilizing advanced nanomaterials, including nanoparticles and metal–organic frameworks, to enhance the sensors' efficiency. Gold nanoparticles are highlighted as particularly effective in this context, with specific nanosensors showing promising results in pesticide detection. This work contributes to the broader efforts in sensor development, offering insights valuable across multiple scientific disciplines.[25]

The quantitative determination of pesticide residues utilizing electrochemical sensors is primarily facilitated through advanced electroanalytical methodologies such as voltammetry and amperometry. These techniques are predicated on measuring the electrical current resulting from the redox transformations of pesticide molecules adsorbed on the electrode's interface. Achieving a high degree of specificity for distinct pesticides is frequently realized by strategically modifying the electrode surface with either biological or synthetic receptors that exhibit a pronounced affinity for the target pesticide entities. A notable approach involves integrating enzymatic systems capable of catalyzing specific reactions with the pesticide molecules, thereby generating amplified electrochemical signals. This enzymatic amplification is instrumental in the ultra-sensitive

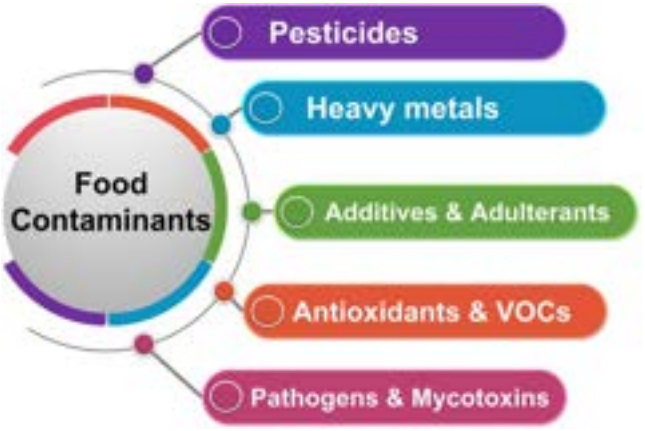

Figure 2. Commonly occurring food contaminants.

detection of pesticide traces, achieving detection limits significantly lower than conventional methods. The advent of nanotechnology has precipitated significant advancements in this arena, markedly enhancing the sensitivity and specificity of these sensors. The incorporation of nanomaterials not only expands the electrode's effective surface area but also facilitates a more efficient electron transfer process. This nanotechnology-driven enhancement is pivotal for the electrochemical detection of pesticides, even at trace levels. The synergy between electroanalytical techniques and nanotechnology has ushered in a new epoch of highly sensitive, selective, and rapid pesticide detection methodologies.[26] Table I delineates a comprehensive list of recently reported pesticide sensors, showcasing cutting-edge developments in electrochemical detection.

Heavy metals.—Meng et al. address the critical issue of heavy metal contamination in food, underscoring its threat to food safety and human health due to bioaccumulation and toxicity, even at minimal concentrations. Their work highlights the efficacy of electrochemical sensors in detecting heavy metals, attributing their success to the sensors' flexibility, selectivity, and accuracy. They explore the advancements in electrochemical sensors, particularly those with electrodes modified by various materials, including inorganic nanoparticles, organic metal-organic frameworks, and biomaterials like nucleic acid aptamers. Meng et al. propose Fe_3O_4/graphene/nucleic acid as an optimal material combination for electrode modification, aiming for sensitive, selective, and economically viable heavy metal detection in foods.[47]

The detection of heavy metals through electrochemical sensing techniques is intricately linked to their unique redox characteristics, which facilitate precise identification and quantification. Anodic stripping voltammetry (ASV) emerges as a cornerstone among these techniques, employing a strategy where metal ions are pre-concentrated onto the electrode surface, followed by their electrochemical oxidation or reduction. This process generates a measurable current directly proportional to the metal ion concentration, enabling accurate quantification. The advent of nanotechnology has significantly propelled the field forward, with nanomaterials such as gold nanoparticles and graphene being utilized as electrode modifiers to enhance the sensitivity and selectivity of electrochemical sensors. These nanomaterials amplify the electrochemical activity at the sensor interface and promote the accumulation of metal ions, facilitating the detection of heavy metals down to ppb levels. This enhancement is crucial for the sensitive detection required in environmental monitoring and food safety applications, where even trace amounts of heavy metals can pose significant health risks. Implementing such nanotechnology-driven advancements has led to a leap in the capabilities of electrochemical sensors, offering unprecedented sensitivity and selectivity in detecting heavy metals. The recent literature on this subject showcases a variety of sensor designs that leverage these advanced materials and techniques,

Table I. A comprehensive list of recently reported pesticide sensors.

Electrochemical sensor	Pesticide	Method	Linear range	LOD	Food sample	References
CuMn-LDH	Trichlorophenol	DPV	0.02–289.2 μM	2.6 nM	Water and fish	27
F-HNT@Bi_2S_3	Diethofencarb	i-t	0.0053–526.62 μg l^{-1}	0.0032 μg L^{-1}	Tomato skin and water	28
$SnSe_2$-NC	Carbendazim	i-t	0.002–139.38 μM	0.67 nM	Water and vegetable extracts	29
$PrVO_4$@NiFe-LDH	Diphenylamine	DPV	0.005–226.26 μM	1 nM	Apple and water	30
DGNR	Parathion methyl	DPV	0.01–25.0 μM	4.3 nM	Water and tomato juice	31
Gd_2O_3/f-CNS	Carbendazim	DPV	0.5–552 μM	9 nM	Water, paddy, aubergine, orange, and tomato	32
FeMn-LDH/WC	Diphenylamine	DPV	0.01–183.34 μM	1.1 nM	Apple and water	33
$MnCo_2O_4$/GCN	Trichlorophenol	DPV	0.01–1720 μM	6.8 nM	Water	34
CQDs/AgNs/SDS	Nitenpyram	DPV	0.1–20 nM	1.5 nM	Tomatoes and paddy	35
$Pr_2(WO_4)_3$/RGO	Fenitrothion	i-t	0.01–313 μM	0.0054 μM	Water	36
AChE-NF/$MnCo_2O_{4.5}$HoQS-MPs	Carbaryl	DPV	0.1 pM to 10 nM	1.58 × 1014 M	Pakchoi	37
	Methamidophos		0.1 pM to 10 nM	1.66×10^{-14} M		
	Monocrotophos		0.1 pM to 100 nM	1.82×10^{-14} M		
WS_2-PDA	Paraoxon ethyl	DPV	0.01–521.34 μM	0.0021 μM	Water and food	38
AChE/CS-GO/GO/CNFs	Chlorpyrifos	SWV	25–1000 nM	2.2 nM	Water and fruit juice	39
CRL@MAC-ZIF-8/chitosan	Methyl parathion	CV	0.5–114 μM	0.06 μM	Water	40
	Chlornitrofen		1–40 μM	0.03 μM		
3D CB-PLA	Carbendazim	SWV	0.5–40.0 μM	0.091 μM	Honey	41
3D Gpt-PLA	Carbendazim	SWV	0.5–50.0 μM	0.03 μM	Honey, milk, orange juice, and water	42
ZnCr–LDH/VC	Diethofencarb	DPV	0.01–228 μM	2 nM	Water and tomato	43
Fe_3O_4/Cu-MOF	Thiram	SWV	10.0 nM–3.0 μM	0.15 nM	Fruit, vegetables, and water	44
AChE/Ag@CuO/PANI	Paraoxon-ethyl	DPV	5–100 pM	11.35 pM	Banana, tomato, and soil	45
Mo_2C@NiMn-LDH	Carbendazim	DPV	0.001–232.14 μM	0.2 nM	Water and vegetable extracts	46

highlighting the ongoing innovation and refinement in the electrochemical detection of heavy metals. These recently reported heavy metal sensors, illustrating the cutting-edge sensor technology and application, are comprehensively listed in Table II, providing a valuable resource for researchers and practitioners alike in navigating the latest developments and employing the most effective sensors for their specific needs.

Pathogens and mycotoxins.—The electrochemical detection of pathogens and mycotoxins in food products represents a sophisticated analytical domain capitalizing on bio-recognition elements for high specificity and sensitivity. In the detection of pathogens, elements such as antibodies, aptamers, or peptide sequences are employed for their ability to selectively bind to antigens on the pathogen surface. The subsequent formation of this bio-complex can be electrochemically quantified through techniques like impedance spectroscopy, which monitors changes in electrical impedance at the electrode surface or via direct electron transfer in enzymatic labels. This methodology affords the precise and sensitive identification of pathogens, serving as an indispensable tool for the rapid screening of foodborne pathogens to uphold food safety standards.[68]

Gayathri et al. explore the rising consumer demand for processed and packaged foods and the consequent imperative for food industries to ensure these products are contamination-free to prevent health hazards. They highlight the criticality of maintaining stringent process controls and quality checks throughout food production stages to avert foodborne diseases caused by pathogens, mycotoxins, and other contaminants. The authors critique conventional detection methods for their lengthy durations and complexity, advocating for using rapid, sensitive, and selective biological sensors, particularly nanosensors. Their work discusses the advancements in nanotechnology-based biosensors, emphasizing their applications in detecting food contaminants and their significant potential in improving food safety and quality.[69]

The approach often involves immunoassay-based methodologies for mycotoxin detection, where antibodies specific to the mycotoxin of interest are immobilized on the electrode surface. The electrochemical quantification of mycotoxin-antibody interactions is facilitated through advanced techniques such as differential pulse voltammetry (DPV) or square wave voltammetry (SWV). These techniques are adept at measuring the current fluctuations resulting from the mycotoxin binding event, thus enabling the detailed monitoring of mycotoxin concentrations in foodstuffs. When paired with the inherent sensitivity of electrochemical detection modalities, the highly specific antibody-mycotoxin interactions provide a robust framework for the effective surveillance of mycotoxin levels, thereby playing a crucial role in mitigating mycotoxin-induced health risks. This integrative approach, leveraging the synergy between bio-recognition specificity and electrochemical sensitivity, underlines the advanced capabilities of electrochemical sensors in the concurrent detection of pathogens and mycotoxins within food matrices. The detailed exploration and comparison of sensors designed for these purposes are encapsulated in Table III, showcasing the forefront of current research and development efforts in enhancing food safety through electrochemical sensing technologies.

Monitoring of food quality and freshness.—Electrochemical sensors have become pivotal in the comprehensive monitoring of food quality and freshness, playing a critical role in assessing various physicochemical parameters that directly impact food safety, nutritional value, and consumer acceptance. Through their advanced electrochemical detection mechanisms, these sensors offer unparalleled sensitivity and specificity in analyzing food products for attributes such as pH and acidity, antioxidant capacity, oxidative rancidity, and VOCs. Applying electrochemical sensors in these domains is instrumental in ensuring the integrity of the food supply chain, from production to consumption.

pH and acidity.—Measuring pH and acidity in food products is paramount, as these parameters significantly influence taste, texture, microbial stability, and overall food quality. Electrochemical sensors

Figure 3. Major domains for ensuring the integrity of the food supply chain.

Table II. A comprehensive list of recently reported heavy metal sensors.

Electrochemical sensor	Heavy metal	Method	Linear range	LOD	Food sample	References
BCN-Nafion	Cd	SWASV	1–150 $\mu g\ l^{-1}$	0.41 $\mu g\ l^{-1}$	Chard	48
	Pb		2–150 $\mu g\ l^{-1}$	0.93 $\mu g\ l^{-1}$		
Fe_3O_4@SiO_2	Cd^{2+}	DPSV	0.1–100 μM	0.0561 μM	Milk	49
	Pb^{2+}		0.1–80 μM	0.0165 μM		
	Cu^{2+}		0.1–80 μM	0.0794 μM		
	Hg^{2+}		0.1–100 μM	0.0567 μM		
Aptasensor-T-Hg^{2+}-T pairs and exonuclease III assistance	Hg^{2+}	DPV	1 nM–10 μM	0.16 nM	Water	50
TT-COF(Zn)/NH_2-CNTs	Hg^{2+}	DPV	0.01–2 mM	1.20 μM	Water	51
	I^-			6.82 μM		
CB-COF	Zn^{2+}	DPASV	0.009–1100 nM	0.003 nM	Honey, rice, tomato, tea, and fish	52
	Cd^{2+}		0.005–1100 nM	0.002, nM		
	Pb^{2+}		0.003–1100 nM	0.001 nM		
	Hg^{2+}		0.001–1100 nM	0.0003 nM		
NH_2–$Ti_3C_2T_x$/GCE	Hg^{2+}	SWASV	0.5–50 $\mu mol\ l^{-1}$	8.27 $nmol\ l^{-1}$	Water	53
ZrO_2/N-3DPC	Hg^{2+}	DPV	0.1–220 $\mu g\ l^{-1}$	0.062 $\mu g\ l^{-1}$	Seafood and water	54
BiM/GR	Hg^{2+}	DPV	0.02–149 μM	5.0 nM	Water, corn, and fish	55
Pd@Bi_2S_3	Hg^{2+}	DPV	0.049–445 μM	13.5 nM	Water and fish	56
$NiFe_2O_4$/PPy	Pb^{2+}	SWASV	0.1–2.1 μM	3.9 nM	Water	57
CS/RGO/TiO_2	Pb^{2+}	DPV	1–1000 $ng\ l^{-1}$	0.33 $ng\ l^{-1}$	Tea, rice, and preserved egg	58
Co-LTPA	Cd^{2+}	SWASV	0.08–5.8 μM	0.119 nM	Milk, honey, orange juice, water	59
	Pb^{2+}		0.01–6.0 μM	0.279 nM		
ACOP/MWCNT	Cd^{2+}	SWV	9.09–72.9 $\mu mol\ l^{-1}$	0.91 $\mu mol\ l^{-1}$	Water	60
$HoVO_4$/F-BN	Hg^{2+}	DPV	0.02–295.4 μM	5 nM	Water, and fish	61
AuNPs/MWCNT/Chit	Cr(VI)	DPV	0.003–0.1 $\mu g\ l^{-1}$	0.007 $\mu g\ l^{-1}$	Water	62
CPE-K/MWCNT/PPY	Mg^{2+}	I-V	0.1 nM-0.01 mM	97.71 pM	Water	63
Ag_2O/UiO-66	Cd^{2+}	DPSV	0.05–1 μM	0.008 μM	Water	64
	Hg^{2+}		0.01–1.2 μM	0.003 μM		
Fe-Co-P	Cd^{2+}	SWASV	0.1–0.8 μM	8.2×10^{-3} μM	Water	65
α-FeOOH/rGO	As^{+3}	DPV	0.1–10 μgl^{-1}	0.07 μgl^{-1}	Water	66
AuNPs@Zr-MOF	Pb^{2+}	DPV	0.05–1000 $nmol\ l^{-1}$	4.65 $pmol\ l^{-1}$	Rice flour, tea, honey, vermicelli, rice	67

Figure 4. Emerging technologies toward food sensing.

Table III. A comprehensive list of recently reported pathogen/mycotoxin sensors.

Electrochemical sensor	Pathogen/ Mycotoxin	Method	Linear range	LOD	Food sample	References
ITO/P-Mel/PGA/DSS	Shigella flexneri	DPV	1×10^{-6} to 1×10^{-21} mol l^{-1}	7.4×10^{-22} mol l^{-1}	Bread, milk, meat, salad, water	70
SPE/P-Cys@AuNPs	Salmonella enterica serovar typhimurium	DPV	1×10^{-6}–1×10^{-22} mol l^{-1}	6.8×10^{-25} mol l^{-1}	Egg and milk	71
PB@ZIF-8/PDA	Deoxynivalenol	DPV	0.1–5000 pg ml^{-1}	0.0186 pg ml^{-1}	Rice and wheat flour	72
ZrTi-MOF	Deoxynivalenol	Impedimetric	1 fg ml^{-1}–1 ng ml^{-1}	0.24 fg ml^{-1}	Bread and wheat flour	73
tyramide signal amplification	*Staphylococcus aureus*	Chrono-amperometric	12–6.25 $\times$ 10^3 CFU/ml	3 CFU/ml	Water and beef broth	74
Bacterial cell-based SELEX	*Staphylococcus aureus*	Chrono-amperometric	1.9×10^2–2.5×10^4 CFU/mL	39 CFU/mL	Water	75
ALP dual-labeled Fe_3O_4 NPs (IMB)	*Staphylococcus aureus*	Immunosensor	10–10^6 cfu ml^{-1}	2.4 cfu ml^{-1}	Water and pork	76
$CaMn_4O_8$–G–SiO_2	Penicillium italicum	Chrono-amperometric	50–100 μl	0.50 μl	Water	77
$MnCO_3$NS/CF	Ochratoxin A	DPV	1.0×10^{-11}–1.0×10^{-9} mol l^{-1}	2.0×10^{-12} mol l^{-1}	Apple juice	78
CB-G-CPE	Ochratoxin A	DPV	27.6 nM-5.45 μM	0.023 μg ml^{-1}	Wheat matrices	79
Immunoassay- alkaline phosphatase	Zearalenone	DPV	0.125 to 0.5 ng ml^{-1}	0.08 ng ml^{-1}	Cornmeal	80
PEI-rGO/Pt@Au	Zearalenone	DPV	1–1 $\times$ 10^6 pg ml^{-1}	0.02 pg ml^{-1}	Corn	81
MIP/AuNPs/rGNRs	Zearalenone	DPV	1–500 ng·ml^{-1}	0.34 ng·ml^{-1}	Maize flour	82
MIP/Fe_3O_4/GO	Patulin	SWV	0.001 nM−250.0 nM	3.33×10^{-4} nM	Apple juice	83
Aptasensor	Patulin	EC-PEC	5.0×10^{-5}–5.0×10^2 ng ml^{-1}	3.0×10^{-5} ng ml^{-1}	Apple juice and apple puree	84
Poly-adenine-mediated tetrahedral DNA nanostructure	Aflatoxin B1	SWV	1.0 fg ml^{-1} to 1 ng ml^{-1}	0.33 fg ml^{-1}	Corn	85
BGE/MBA/Fe_3O_4-NH_2/pAb-AFB1/BSA	Aflatoxin B1	Impedimetric	0.5–30 μg ml^{-1}	3.79 μg ml^{-1}	Peanuts	86
BSA/Apt/O-VMSF/ITO	Aflatoxin B1	DPV	3 pg ml^{-1} to 3 μg ml^{-1}	2.3 pg ml^{-1}	Peanut and corn	87
ss-HSDNA/AuNPs	Fumonisin B1	CV	0.5–500 ng ml^{-1}	0.14 ng ml^{-1}	Maize flour	88
Apt–Au@Pt	Fumonisin B1	DPV	50 fg/ml to 100 ng ml^{-1}	21 fg/ml	Corn and wheat	89

designed for pH measurement typically operate on potentiometric principles, measuring the potential difference between a reference electrode and a working electrode sensitive to hydrogen ion concentration. This approach directly quantifies acidity levels in a diverse array of food matrices, from beverages to dairy products. Moreover, integrating novel materials and nanotechnologies has led

Table IV. A comprehensive list of recently reported antioxidant/VOC sensors.

Electrochemical sensors	Antioxidants/ VOCs	Method	Linear range	LOD	Food sample	References
$ZnCr_2O_4$	Ascorbic acid	DPV	0.01–126 μM	12.56 nM	Orange juice	93
PrV@g-CN	Quercetin	DPV	0.05–252.0 μM	0.002 μM	Green and black tea	94
$CoPc(OC_8H_9)_8$	Ascorbic acid	DPV	0.1–100 μM	36 nM	Milk	95
NaOH/PGE	Ascorbic acid	DPV	2–200 μM	1.4 μM	Green tea and vitamin c	96
	Gallic acid		1–30 μM	0.6 μM		
CdO/SWCNTs	Caffeic acid	LSV	0.02–200 μM	9.0 nM	Wine and fruit juice	97
CuS@C-c	Ascorbic acid	DPV	0.1–1000.0 μmol/l	0.03 μmol/l	Vitamin C tablets	98
N/Ni SAE	Quercetin	SWV	0.01–0.1 and 1.0—100 μM	3.4 nM	Fruit juices	99
(MOF), $[Zn_2L(OH\text{-}bdc)_2]\cdot 2.5\ H_2O$/RGO	Luteolin	DPV	0.02–14 μM	0.0022 μM	Peanut shell	100
	Quercetin		0.02–14 μM	0.0049 μM	Sophora flower bud	
$CoWO_4$	Quercetin	DPV	0.2–521 μM	0.022 μM	Fruit juice	101
	Rutin		0.2–681 μM	0.018 μM		
Pt-MXene	Quercetin	DPV	0.001–1.0 nM $\times 10^3$	0.92 nM	Orange, apple, and grape juices	102
porous carbon	Hydroquinone	DPV	5.0–1200.0 μM	0.18 μM	Water	103
ZnO@MnO_2-rGO	Hydroquinone	DPV	0.008-to 320 μM	0.0012 μM	Soybean oil, water, orange juice	104
	Catechol		0.008–330 μM	0.001 μM		
ZIF-8@SWCNT- AuNPs/PB	Hexanal	DPV	10^{-16}–10^{-9} M	10^{-16} M	Grapes	105
GPE/ZnO	Formaldehyde	CV	0–100 mM	18 μM	Tofu	106
PdRu/N-SCs	Caffeic acid	DPV	1 nM-15 μM	0.19 nM	Red wine, strawberries, and blueberries	107
Cu@NC	Luteolin	DPV	(0.05–20) $\times 10^{-6}$ mol l^{-1}	5.30 $\times 10^{-8}$ mol l^{-1}	Qingrejiedu granules and shuanghuanglian oral liquid	108
	Baicalein		(0.05–20) $\times 10^{-6}$ mol l^{-1}	9.10 $\times 10^{-8}$ mol l^{-1}		
Co@NCF/MoS_2/MWCNTs	Luteolin	DPV	0.0001–1.3 μM	0.071 nM	Chrysanthemum, peanut shells and honeysuckle	109
3D-printed carbon black	Folic acid	SWV	10 and 200 μmol/l	$\sim$ 5.1 μmol/l	Apple, orange, and coconut water	110
AuNPs/Zn/Ni-ZIF-8—800@graphene	Gliadin	CV	0.1–100 μg ml$-^1$	0.950 μg ml^{-1}	Gluten-free flour, biscuits, cat food, dog food, chicken feed, and pig feed	111
GO-MIP	Folic acid	CV	1.0 $\times$ 10−9–1.0 $\times 10^{-5}$ M	1.0 nM	Spinach, wheat, and tablets	112

to the development of pH sensors with enhanced sensitivity, selectivity, and durability, capable of withstanding the harsh conditions often encountered in food processing environments. Such advancements enable the real-time monitoring of pH and acidity, facilitating the optimization of fermentation processes, the assessment of spoilage risk, and the assurance of product consistency.[90]

Antioxidant capacity and volatile organic compounds (VOCs).—The quantification of antioxidant capacity and the detection of VOCs are paramount in assessing food quality, each serving as a pivotal marker for nutritional value, shelf life, and freshness. Electrochemical sensors, leveraging advanced techniques such as cyclic voltammetry and differential pulse voltammetry, play a critical role in these evaluations by facilitating the direct measurement of electron transfer processes. In the context of antioxidants, these sensors enable the precise quantification of total antioxidant capacity by monitoring the current associated with the oxidation or reduction of antioxidants at the electrode interface. This capability is instrumental in appraising the food's resistance to oxidative processes that precipitate spoilage and degradation, providing essential insights into its shelf life and nutritional content.[91]

Simultaneously, the electrochemical detection of VOCs, which encompass a broad spectrum of compounds integral to the aroma and flavor of food or indicative of spoilage, employs selective sensing materials tailored to the unique electrochemical attributes of these compounds. The interaction with specific VOCs results in a measurable change in the sensor's electrical properties, allowing for the selective identification and quantification of VOCs related to ripening, spoilage, and fermentation processes. This dual approach to monitoring antioxidant capacity and VOCs underscores the versatility and efficacy of electrochemical sensors in ensuring food quality and freshness.[92]

Recent advancements in sensor technology, including the refinement of electrode modification techniques with metal nanoparticles, carbon nanotubes, conductive polymers, metal-oxide semiconductors, and nanocomposite materials, have markedly improved these sensors' sensitivity, specificity, and stability. These innovations enhance the analytical performance in complex food matrices and contribute significantly to quality control measures, facilitating the comprehensive analysis of antioxidant levels and VOC profiles. Electrochemical sensors are at the forefront of efforts to maintain and enhance food product standards across the industry by providing robust, non-invasive tools for monitoring critical quality indicators. The intricate design and application of sensors tailored for antioxidant capacity and VOC detection are detailed in Table IV, illustrating the state-of-the-art electrochemical sensing technologies for food quality assessment.

Oxidative rancidity.—Oxidative rancidity is a detrimental process affecting fats and oils, characterized by forming off-flavors, off-odors, and potentially harmful oxidation products. Detecting early signs of oxidative rancidity is critical for maintaining the quality and

safety of lipid-containing foods. Electrochemical sensors targeting the markers of oxidative rancidity, such as peroxides and secondary oxidation products like aldehydes and ketones, offer a promising solution for the early detection of rancidity. These sensors typically employ voltammetric or amperometric detection methods, enabling the identification and quantification of specific oxidation compounds. The advancement in sensor technology, including the design of electrodes with increased surface area and catalytic activity, has improved these sensors' detection limits and response times, making them invaluable tools for the quality assurance of oils, dairy products, and other susceptible food items.[113]

Authentication and traceability.—In the contemporary landscape of food safety and quality assurance, the role of electrochemical sensors extends beyond the mere detection of contaminants and quality indicators to encompass the critical realms of authentication and traceability. This application is particularly significant in combatting food fraud, verifying geographic origin, ensuring accurate labeling, and authenticating species. Electrochemical sensors, with their inherent sensitivity and specificity, are at the forefront of technological advancements designed to safeguard the integrity of the food supply chain, providing consumers and regulatory bodies with the tools necessary to enforce transparency and authenticity in food products.[114]

Food fraud detection.—Food fraud, encompassing practices such as adulteration, mislabeling, and substitution, significantly jeopardizes consumer health and erodes trust in the food industry. Electrochemical sensors are powerful tools for addressing these challenges by allowing direct analysis of food composition and the identification of unexpected or unauthorized additives and substances. These sensors, often equipped with MIPs or specific biological recognition elements, are particularly adept at detecting adulterants in frequently targeted foods like milk and olive oil. The quantitative measure provided by the electrochemical signals generated during detection allows for swift and accurate identification of adulteration, which is crucial for maintaining food integrity and compliance with safety regulations.

Recent instances of food fraud detection highlight the growing need for such technologies. For example, a notable case involved the detection of horse meat being sold as beef across several European countries, a significant incident that highlighted the vulnerabilities in the food supply chain.[115] Another case involved honey where cheap sweeteners were added and then sold as 100% natural honey, misleading consumers and undercutting honest producers.[116] These instances not only underline the prevalence of food fraud but also demonstrate the essential role of advanced detection methods like electrochemical sensors in preventing such deceptive practices and ensuring the authenticity and safety of food products on the market.[114]

Geographic origin determination.—Determining the geographic origin of food products is a key aspect of enforcing labeling regulations, protecting regional specialties, and preventing the sale of counterfeit goods. Electrochemical sensors play a critical role in the verification of geographic origin by detecting specific markers or isotopic signatures that are unique to particular regions. These sensors analyze the elemental or molecular composition of food products, enabling the differentiation between products of various origins. The capability to identify unique electrochemical profiles associated with geographic-specific factors such as soil types, climatic conditions, or cultivation practices allows for precise origin determination.

The ability of electrochemical sensors to accurately assess these unique profiles significantly enhances the traceability of the food supply chain and supports the authenticity of products with labeled geographical indications. For example, wines from a specific region may contain unique isotopic ratios reflective of the local soil and climate conditions, and similar principles apply to products like coffee, spices, and cheeses that are often labeled based on their region of origin. By leveraging the sensitivity of electrochemical sensors to these subtle compositional differences, stakeholders can ensure compliance with regional certifications and combat the sale of falsely labeled products, thereby maintaining market integrity and consumer trust.[117]

Labeling verification.—Accurate food labeling is crucial for ensuring consumer information and preventing food fraud. Electrochemical sensors are instrumental in the verification of food labels, particularly in analyzing the composition of food items rapidly and accurately. These sensors are adept at confirming the presence and exact concentrations of specific compounds listed on food labels, such as vitamins, minerals, and allergens. Their application in labeling verification not only ensures adherence to food labeling regulations but also helps in identifying and addressing mislabeled products, thereby bolstering consumer trust in the accuracy of food labels. This method primarily focuses on validating the truthfulness of information provided on food packaging, which includes a detailed breakdown of ingredients and nutritional content.[6]

Species authentication.—In contrast, species authentication targets a different aspect of food integrity, focusing on preventing the substitution or mislabeling of meat, fish, and other products at the species level. Electrochemical sensors excel in species authentication by detecting species-specific biomarkers, such as DNA sequences or proteins. Techniques like electrochemical DNA biosensors utilize the hybridization of target DNA sequences to complementary probes fixed on the sensor's surface. This interaction produces an electrochemical signal that clearly identifies the species, facilitating rapid and unequivocal verification. Species authentication is critical for maintaining the overall integrity of the food supply chain and protecting consumers against the risks and fraud associated with incorrectly labeled species.[118]

Allergen detection.—Detecting allergens in food products is a critical aspect of food safety, essential for protecting consumers with food allergies and complying with labeling regulations. Electrochemical sensors have emerged as a powerful technology for the sensitive, specific, and rapid detection of food allergens, including gluten, peanuts, and dairy. These sensors utilize various electrochemical detection methods to identify allergenic proteins or residues that can pose health risks to susceptible individuals. By leveraging advancements in materials science, biotechnology, and electrochemistry, these sensors offer a promising approach to enhancing allergen management in the food industry.

Detecting food allergens such as gluten, peanuts, and dairy proteins through electrochemical sensors represents a sophisticated and precise analytical approach, catering to the pressing need for sensitive allergen identification in the food industry. These sensors, designed to detect gluten in wheat, barley, rye, peanut allergens, and dairy proteins like casein and whey, leverage bio-recognition elements, including antibodies and aptamers that exhibit high specificity towards these allergens. These elements are immobilized on the sensor's electrode surface, where their interaction with the target allergen induces a quantifiable electrochemical change—manifested as alterations in current or impedance—proportional to the allergen concentration.[119]

Recent advances in the field have been catalyzed by integrating nanomaterials and microfabrication technologies into electrode design, significantly enhancing these sensors' sensitivity, selectivity, and user-friendliness. For instance, nanomaterial-enhanced electrodes have drastically improved gluten sensors' performance, achieving detection thresholds as low as a few parts per million (ppm), thereby adhering to stringent regulatory requirements. Similarly, for peanut and dairy allergens, the employment of specific antibodies or DNA aptamers as recognition elements, combined with the application of amperometry, voltammetry, enzymatic

Table V. A compilation of nanomaterials detailing their characteristics and utilization in electrochemical sensors.

Nanomaterial	Properties	Applications in electrochemical sensors
Carbon nanotubes[123] (CNTs)	Exceptional electrical conductivity, mechanical strength, and high surface area.	Facilitate electron transfer, improve sensitivity and selectivity, and allow enzyme or antibody immobilization.
Graphene[124] and Graphene oxide[125]	High surface area, excellent conductivity, and ease of functionalization.	Rapid detection of pesticides, heavy metals, and pathogens due to efficient electron transfer and analyte diffusion.
Metal nanoparticles[126] (Au, Ag, Pt)	Catalytic activity, high surface-to-volume ratio, biocompatibility (particularly Au).	Enhance electrochemical signals, facilitate oxidation/reduction of analytes, and improve biomolecule immobilization for specific detection.
Quantum dots[127] (QDs)	Size-dependent optical and electronic properties, tunable affinity for analytes.	High sensitivity and selectivity, multiplexing capabilities for simultaneous detection of multiple contaminants.
Conductive polymers[128] (Polyaniline, Polypyrrole, Polythiophene)	Electrical conductivity, ability to incorporate functional groups.	Enhance sensitivity, stability, and selectivity by forming a sensitive layer on electrode surfaces.
Magnetic nanoparticles[129]	Superparamagnetic properties, ease of separation, and surface modifiability.	Simplify sample preparation and enhance sensor specificity through magnetic separation and concentration of analytes.
Silica nanoparticles[130]	Porous structure, large surface area, chemical stability.	Serve as carriers for enzymes or antibodies, improving sensor stability and allowing for the design of reusable sensors.
Metal oxide nanoparticles[2]	Specific catalytic properties and high electron communication features.	Detect volatile organic compounds and gases and improve sensitivity and selectivity towards specific analytes.
Nanofibers[131]	Biodegradability, high mechanical strength, and large surface area.	Biocompatible scaffolds for enzyme immobilization, enhancing sensor sensitivity and environmental sustainability.
Nanodiamonds[132]	High surface area, biocompatibility, and unique optical and thermal properties.	Provide stable immobilization platforms for biomolecules, enhancing sensor durability and sensitivity.
Bimetallic nanoparticles[133]	The combination of two metals can enhance catalytic activity and selectivity.	Tailored for specific electrocatalytic reactions, improving the detection limits for challenging analytes.
Nanocomposites [134]	Synergistic properties from combined nanomaterials.	Leverage combined electrical, mechanical, and catalytic properties to enhance overall sensor performance.

amplification, or direct electron transfer mechanisms, facilitates the accurate quantification of trace allergen residues in diverse food products. Moreover, the advent of portable electrochemical sensors, benefiting from microfabrication technology, has revolutionized the on-site screening of foods for peanut contamination, enhancing the safety protocols for individuals with severe allergies. The continuous refinement of sensor technologies, including the adoption of conductive polymers and nanocomposites, further underscores the advancements in achieving greater analytical performance. This progress bolsters the electrochemical sensors' ability to monitor allergen presence with unprecedented sensitivity and specificity and broadens their applicability across various food matrices. This comprehensive approach to allergen detection underscores the critical role of electrochemical sensing in safeguarding food safety, offering robust solutions for effectively managing allergen-related health risks in sensitive individuals. The innovative strategies and materials employed in the development of these sensors highlight the dynamic evolution of the field, pushing the boundaries of what is achievable in the precise detection of gluten, peanuts, and dairy allergens.[120]

Detection of food additives and adulterants.—Detecting food additives and adulterants is critical to food safety and regulatory compliance. Electrochemical sensors offer a versatile and practical approach for identifying and quantifying various additives and adulterants in food products. Through their advanced electrochemical mechanisms, these sensors provide the sensitivity and specificity required to detect even trace amounts of these substances, ensuring that food products meet safety standards and are free from harmful or unauthorized additives. The development and application of electrochemical sensors for monitoring artificial sweeteners, preservatives, colorants, and illegal additives in food products represent a critical advance in ensuring food safety and regulatory compliance. These sensors leverage the unique electrochemical properties of each compound class, employing tailored recognition elements such as enzymes, MIPs, and specific biomolecules or synthetic receptors to achieve high specificity and sensitivity.

Artificial sweeteners like aspartame, sucralose, and saccharin are scrutinized due to health concerns and consumption limits, necessitating their precise quantification in foods. Electrochemical sensors detect these compounds via specific interactions that induce a measurable electrochemical change, typically through voltammetric or amperometric methods, facilitating the analysis of sweetener content across diverse food matrices.[121]

Similarly, detecting preservatives (sulfites, nitrates, benzoates) and colorants (azo dyes, carotenoids) is paramount for monitoring their adherence to safety standards due to the potential health risks associated with excessive consumption and the regulatory limits on their use. Modified electrodes, integrated with materials that specifically bind to these additives, generate electrochemical signals corresponding to their concentrations, enabling rapid and accurate detection. Furthermore, the identification of illegal additives, such as melamine and non-approved synthetic dyes, is crucial for averting health hazards. Electrochemical sensors designed for this purpose utilize selective detection mechanisms capable of identifying these substances at very low concentrations, thereby offering a potent tool for enforcing food safety regulations.[122]

The collective application of these electrochemical sensing technologies underscores their importance in the comprehensive monitoring of food additives, ensuring that products remain within the safe and legal thresholds for consumption. By integrating advanced materials and specific recognition strategies, these sensors provide a robust platform for the rapid, sensitive, and precise analysis of a broad spectrum of food additives, contributing significantly to safeguarding public health and the integrity of the food supply chain.

Recent Advances in Electrochemical Sensor Technologies

Nanomaterial-based sensors.—The last three years have witnessed remarkable progress in the field of electrochemical sensor technologies, particularly through the integration of nanomaterials. Nanomaterials offer unique properties such as high surface area, excellent electrical conductivity, and specific surface reactivity, which significantly enhance the performance of electrochemical

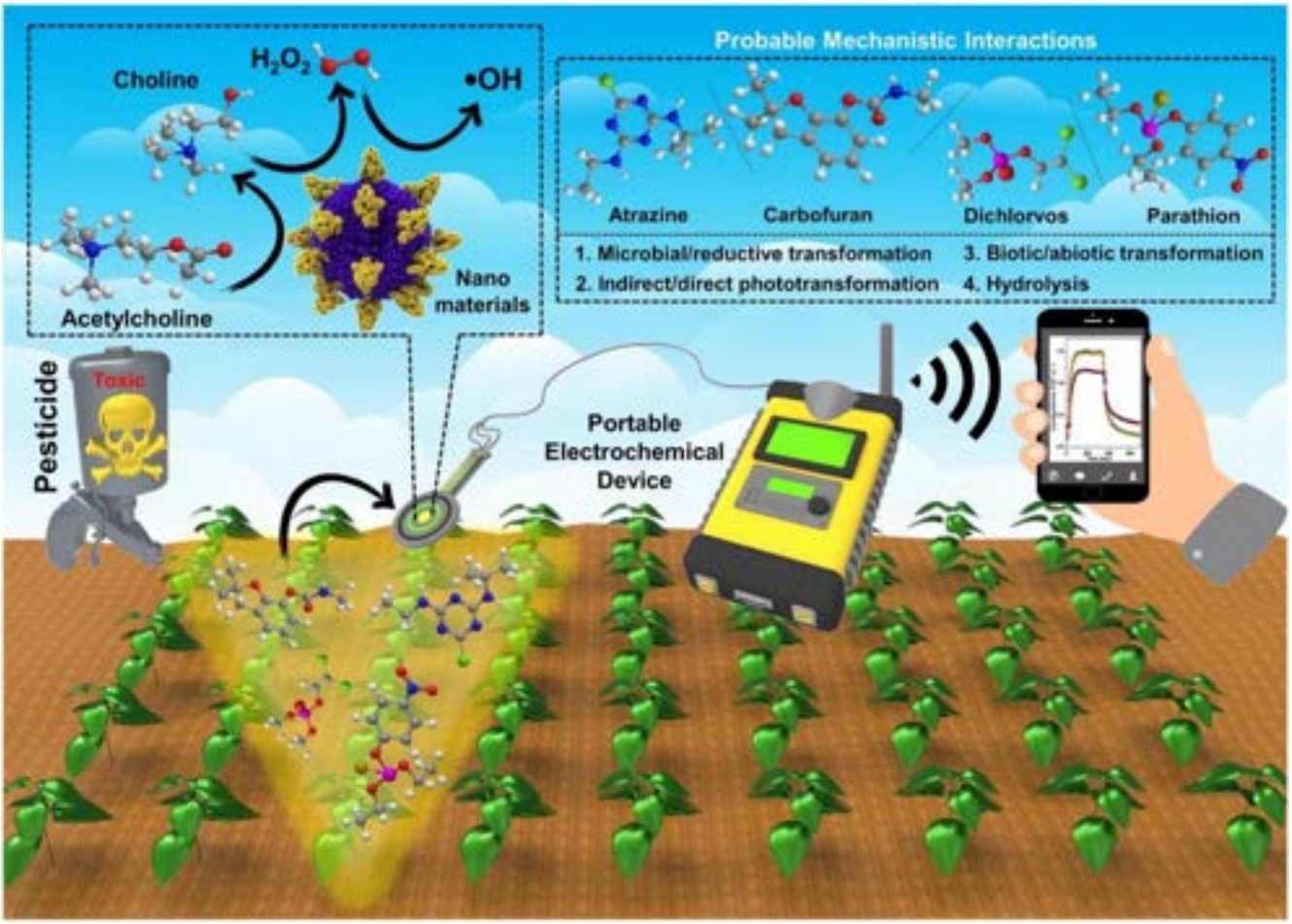

Figure 5. Portable electrochemical sensing methodologies for on-site detection of pesticide residues in fruits and vegetables. Adapted with permission from the publisher.[135].

sensors. These advances have led to the development of highly sensitive, selective, and rapid sensors for a wide range of applications in food safety and quality monitoring, as shown in Table V.

Miniaturization and portable devices.—Umapathi et al. address the escalating threat of pesticide residues to ecosystems and human health, driven by excessive synthetic pesticide use in agriculture. They highlight electrochemical sensors and biosensor platforms as efficient analytical tools for detecting pesticides, emphasizing their synergistic design, ease of use, high sensitivity, and selectivity. The work mainly focuses on the innovation of portable electrochemical devices for point-of-care and on-site detection of pesticide residues in produce, as shown in Fig. 5.[135] The movement towards miniaturization and the creation of portable devices in the realm of electrochemical sensor technology signifies a transformative development in the availability of sophisticated analytical tools for field-based and real-time testing, especially pertinent to the domain of food safety and quality monitoring. This trend responds to the critical need for immediate, cost-effective, and user-friendly detection methods capable of identifying contaminants and evaluating food quality directly at the point of production, processing, or sale, bypassing the logistical and temporal constraints associated with conventional laboratory analyses. Miniaturized electrochemical sensors and portable devices capitalize on breakthroughs in microfabrication techniques, nanomaterials, and digital technology, incorporating these advances into compact, versatile, and powerful tools. These innovations enable the integration of complex electrochemical sensing capabilities with microfluidics, digital signal processing, and wireless connectivity, facilitating their use by individuals without specialized training. The capacity for immediate detection and analysis of food safety hazards or quality parameters on-site dramatically improves the efficiency and effectiveness of food safety management systems, contributing to the prevention of foodborne diseases and minimizing waste due to spoilage. Moreover, developing these portable, easy-to-use devices democratizes the technology, making sophisticated testing accessible to a broader range of stakeholders within the food supply chain, including producers, processors, regulators, and consumers. As the trend towards miniaturization and portability progresses, it is poised to revolutionize the approach to food safety and quality assurance, enabling a more proactive and preventive strategy for managing the risks associated with the global food industry.

Signal amplification techniques.—Signal amplification techniques in electrochemical sensor technologies have significantly enhanced sensors' sensitivity and detection limits, enabling the identification of trace levels of analytes with unprecedented precision. These advancements are pivotal in detecting low-abundance substances, such as specific pathogens, toxins, or allergens in food samples, where their presence, even at minimal concentrations, can pose serious health risks. Amplification strategies employ various innovative approaches to increase the measurable signal output relative to the background noise, thereby improving the sensor's overall performance.[136] One standard method involves using enzymatic amplification, where enzymes conjugated to the detection probe catalyze reactions that produce electroactive species, leading to a substantial increase in the electrochemical signal. This method leverages enzymes' high specificity and catalytic activity to achieve

significant signal enhancement. Another approach is nanoparticle-based amplification, wherein metal nanoparticles or quantum dots, acting as carriers for multiple signal molecules, are bound to the target analyte. These particles facilitate a higher load of signal-producing entities per target molecule, amplifying the detected signal.[137]

Furthermore, developing redox cycling techniques, which involve the repeated oxidation and reduction of electroactive species within a confined space near the sensor surface, has proven effective in enhancing signal output. This is achieved by constructing electrode configurations that allow for efficient electron transfer and recycling of redox species, leading to a substantial amplification of the signal.

In addition, integrating conductive polymers and carbon nanomaterials, such as graphene and carbon nanotubes, into sensor designs has also been explored for signal amplification. These materials can increase the effective surface area of the electrodes and facilitate the rapid transfer of electrons, thereby enhancing the electrochemical signal. Moreover, the application of molecular amplification strategies, including the use of DNA or RNA amplification techniques like PCR (polymerase chain reaction) or isothermal amplification, directly into electrochemical sensors, has opened new avenues for the ultra-sensitive detection of genetic markers associated with pathogens or genetically modified organisms in food.[138]

Integration with electronic systems and data analysis software.—The work depicted in Fig. 6 addresses the public health challenge posed by adverse food reactions, including food allergies, sensitivities, and autoimmune reactions like celiac disease, which affect 5%–15% of the population. To combat the difficulty of avoiding problematic foods, especially with the prevalent consumption of prepared foods and dining out, the authors developed a portable, point-of-use detection technology named integrated exogenous antigen testing (iEAT). The iEAT system, comprising a disposable antigen extraction device and an electronic keychain reader, enables rapid sensing and communication, optimized to detect major food antigens in peanuts, hazelnuts, wheat, milk, and eggs. It achieves high-detection sensitivities (e.g., 0.1 mg kg^{-1} for gluten, surpassing the regulatory limit of 20 mg kg^{-1}) within less than 10 minutes. Demonstrating its utility under real-world conditions, iEAT successfully identified hidden food antigens in "gluten-free" items in restaurants, offering a promising tool for consumers, clinicians, food industries, and regulators to improve food safety.[139]

Integrating electrochemical sensors with electronic systems and data analysis software marks a transformative advancement in the field, enhancing these devices' functionality, usability, and intelligence. This integration is pivotal in translating complex electrochemical signals into actionable insights, thereby broadening the scope of applications for electrochemical sensors, especially in food safety and quality monitoring. Electronic systems, including microcontrollers and digital signal processors, serve as the backbone for modern electrochemical sensors, facilitating precise control over measurement parameters, signal processing, and data acquisition. These systems enable the real-time monitoring of electrochemical reactions, ensuring high accuracy and reproducibility of results. Incorporating electronic components allows for the miniaturization of sensors, making them more portable and convenient for on-site testing.

Data analysis software plays a crucial role in interpreting the data collected by electrochemical sensors, employing sophisticated algorithms and machine learning techniques to identify patterns, trends, and anomalies in the sensor outputs. This software can automatically compare sensor readings against predefined thresholds or standards, making it easier to identify the presence of contaminants or assess the quality of food products. Advanced data analytics enable the prediction of food spoilage, the verification of authenticity, and the detection of adulteration with greater confidence and precision. Furthermore, integrating electrochemical sensors with wireless communication technologies, such as Bluetooth, Wi-Fi, and NFC, enables the seamless transmission of data to smartphones, tablets, or cloud-based platforms. This connectivity facilitates the remote monitoring and management of food safety protocols, allowing stakeholders across the food supply chain to access real-time information, make informed decisions, and respond promptly to potential issues.

Surface modification techniques.—As shown in Fig. 7, Kunpatee et al. have engineered a disposable electrochemical sensor with heightened sensitivity for detecting carbaryl, fenobucarb, and carbosulfan pesticides, utilizing a MnO_2-GNPs/SPCE. The sensor demonstrated a linear detection range for carbaryl (1–40 μM), fenobucarb (5–150 μM), and carbosulfan (50–600 μM) with impressively low detection limits of 0.30 μM for carbaryl, 1.30 μM for fenobucarb, and 14.90 μM for carbosulfan. In tests for simultaneous detection, it showed linear ranges of 1–30 μM for carbaryl, 5–80 μM for fenobucarb, and 50–400 μM for carbosulfan, with detection limits of 0.30 μM, 1.40 μM, and 15.15 μM, respectively.

Surface modification techniques for electrochemical sensors have significantly advanced the field of food safety and quality monitoring, enhancing these devices' sensitivity, selectivity, and stability.[141] These techniques involve altering the surface properties of the sensor electrodes to improve their interaction with specific analytes, thereby increasing the sensor's performance in detecting contaminants, adulterants, and quality indicators in food products.

One of the critical approaches in surface modification is using self-assembled monolayers (SAMs) on electrode surfaces. SAMs provide a well-defined, organized layer of molecules that can be tailored to possess specific chemical functionalities, enabling the selective binding of target analytes. This specificity is crucial for detecting low-abundance compounds amidst complex food matrices, ensuring accurate and reliable sensor responses. Another prominent technique involves the deposition of nanomaterials, such as metal nanoparticles, carbon nanotubes, graphene, and quantum dots, onto electrode surfaces. These nanomaterials offer unique electronic, catalytic, and surface properties that enhance the sensor's electrochemical activity. By facilitating faster electron transfer and providing a larger surface area for analyte interaction, nanomaterials significantly amplify the sensor's signal, allowing for the detection of trace levels of food contaminants and quality markers. Electrode surfaces can also be modified by immobilizing biological recognition elements, including enzymes, antibodies, DNA sequences, and aptamers. These biomolecules confer high specificity towards target analytes, transforming the sensor into a highly selective platform that distinguishes specific substances within complex food samples. The immobilization techniques ensure that these biomolecules retain their activity and stability over time, contributing to the durability and repeatability of the sensor's measurements. Polymeric coatings represent another surface modification strategy, where conductive polymers or polymer composites are applied to the sensor surface. These coatings can be engineered to interact selectively with specific analytes or to create a barrier against interfering substances, enhancing the sensor's selectivity and sensitivity. Moreover, polymeric coatings can provide a protective layer for the sensor, extending its lifespan and usability in harsh food processing environments.

Molecularly imprinted polymers (MIPs).—MIPs represent a cutting-edge advancement in the field of sensor technology, particularly within the context of electrochemical sensors for food safety and quality monitoring. MIPs are synthetic polymers that are engineered through a process known as molecular imprinting, where the polymer matrix is formed in the presence of a template molecule, which is subsequently removed, leaving behind a cavity that is complementary in shape, size, and functional groups to the target molecule.[142] This unique fabrication process endows MIPs with highly specific recognition sites that are tailor-made for the selective binding of specific analytes, mimicking the selective binding

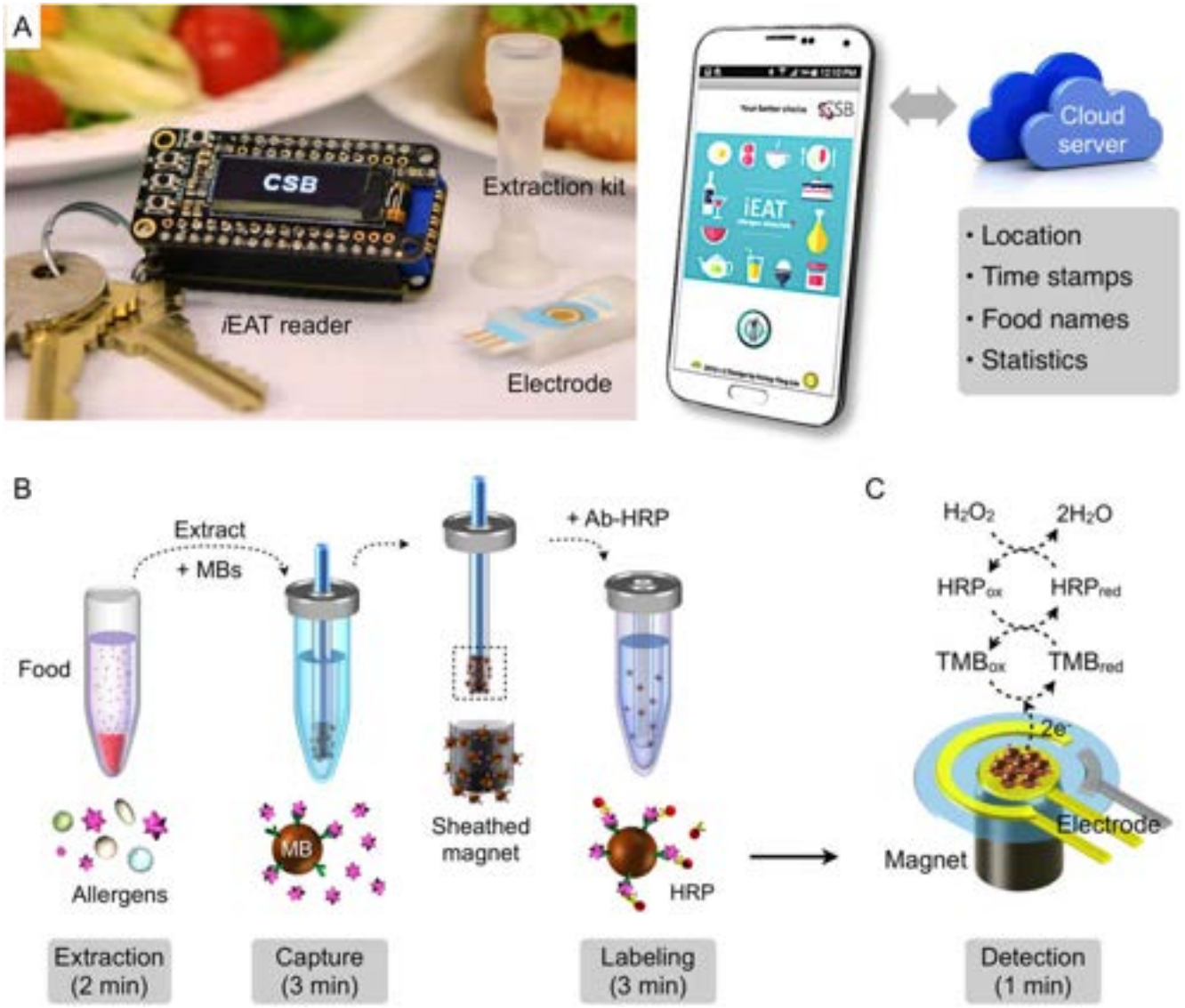

Figure 6. Overview of the iEAT On-Site Allergen Detection System: (A) Comprises a pocket-sized detector, electrode chip, and a disposable allergen extraction kit, with smartphone connectivity for system operation and data syncing to a cloud server. (B) Antigen Extraction: Utilizes magnetic beads for antigen capture, followed by labeling with HRP-conjugated antibodies. (C) Signal Detection: Involves the addition of HRP-coated MBs to electron mediators (TMB, 3,3′,5,5′-tetramethylbenzidine) on the electrode, where HRP catalyzes TMB oxidation. Adapted with permission from the publisher[139].

properties of biological receptors such as antibodies and enzymes but with superior stability and robustness.[143]

As shown in Fig. 8, the scientific principle underlying the development of MIPs involves the formation of pre-polymerization complexes between the template molecule and functional monomers through non-covalent interactions such as hydrogen bonding, ionic interactions, and hydrophobic effects. Following the initiation of polymerization, a highly cross-linked polymer matrix is formed, encapsulating the template within this structure. The subsequent removal of the template molecule, often achieved through solvent extraction or thermal decomposition, yields a polymer matrix with sterically and chemically complementary cavities to the target analyte. These imprinted sites facilitate the selective re-binding of the target molecule, allowing for its specific detection and quantification in complex matrices.

In the realm of electrochemical sensors, MIPs serve as highly selective recognition elements that are integrated into the sensor's electrode surface. Incorporating MIPs enhances the sensor's specificity by enabling the selective capture of target analytes from complex food samples, thereby minimizing the interference from other substances present in the matrix. The selective binding of the analyte to the imprinted sites alters the electrochemical properties at the electrode interface, such as charge transfer resistance or current flow, which can be quantitatively measured, providing a direct correlation to the concentration of the target analyte. MIPs offer several advantages over traditional biological recognition elements, including enhanced stability under harsh chemical and thermal conditions, reusability, and cost-effectiveness. These properties make MIP-based electrochemical sensors particularly attractive for food safety and quality monitoring applications, where the detection of contaminants, adulterants, and quality markers requires robust, reliable, and sensitive analytical tools. Furthermore, the versatility in the design and synthesis of MIPs allows for their application in detecting a wide range of target molecules, from small organic compounds to proteins and pathogens, making them invaluable tools in the ongoing efforts to ensure the safety and integrity of the food supply.

Bioelectrochemical sensors.—In bioelectrochemical sensors, exploring and utilizing diverse biomaterials for biorecognition elements significantly enhance the sensors' specificity, sensitivity, and versatility. These biomaterials include a wide array of biological

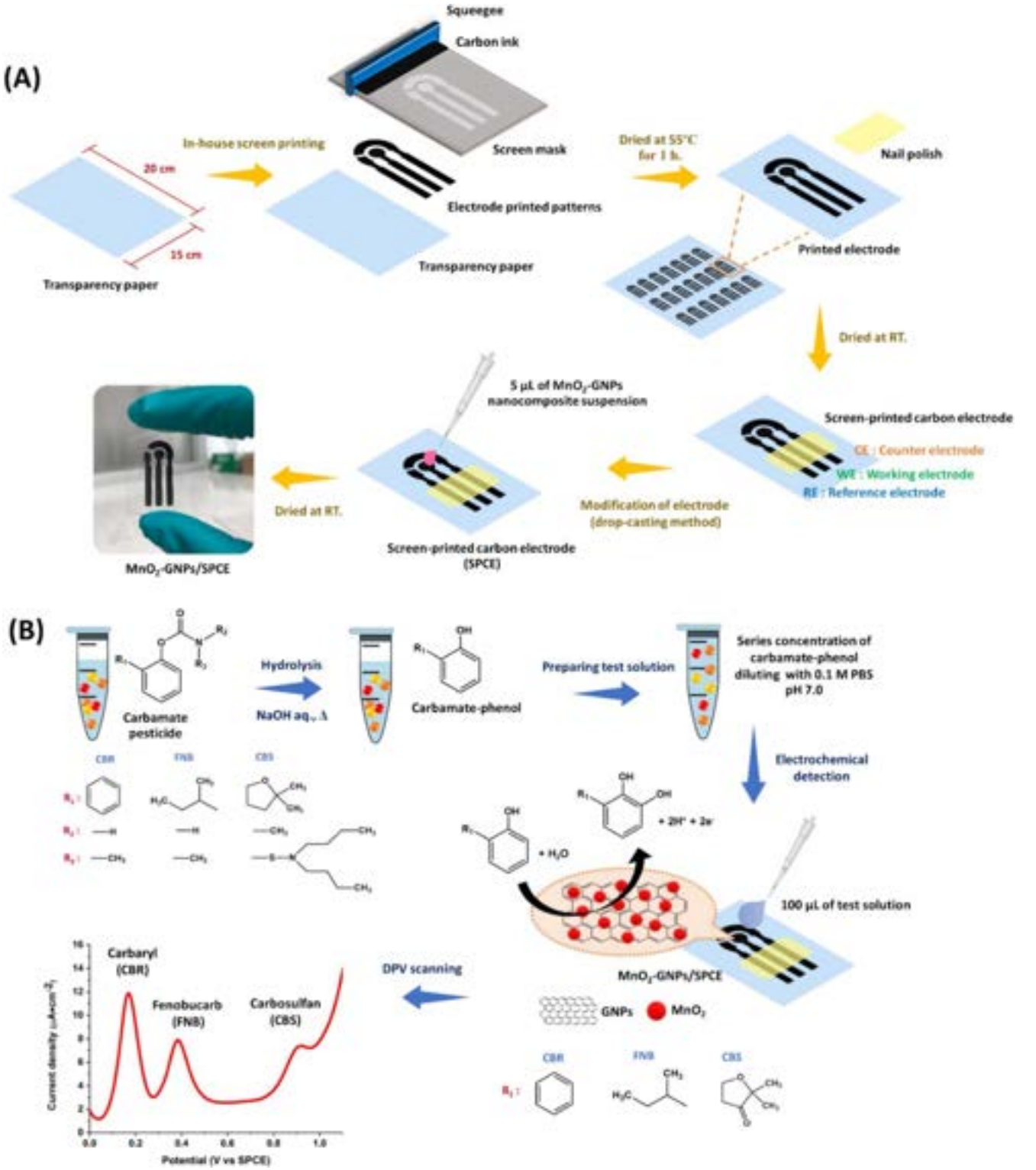

Figure 7. (A) Visual of the fabrication processes and (B) electrochemical measurement of MnO_2-GNPs/SPCE sensor for the detection of carbaryl, fenobucarb, and carbosulfan. Adapted with permission from the publisher[140].

entities such as enzymes, antibodies, nucleic acids, and whole cells, each offering unique advantages for detecting various analytes relevant to food safety and quality.

The work shown in Fig. 9 by Meng et al. introduces a metal-organic framework (MOF)-based bio-bar code material utilized for the first time to develop an electrochemical sensor for the sensitive detection of streptomycin (STR). The sensor achieves dual-signal amplification by leveraging MOF-based bio-bar codes and enzyme-assisted target recycling, leading to highly sensitive STR detection. The sensor's surface is prepared by immobilizing a mixed monolayer of thiolated complementary DNA/aptamer duplexes and 6-mercapto-1-hexanol on a gold nanoparticle-modified screen-printed carbon electrode. Upon target STR binding, the aptamer is efficiently displaced from the DNA duplex by the Exo I enzyme, allowing

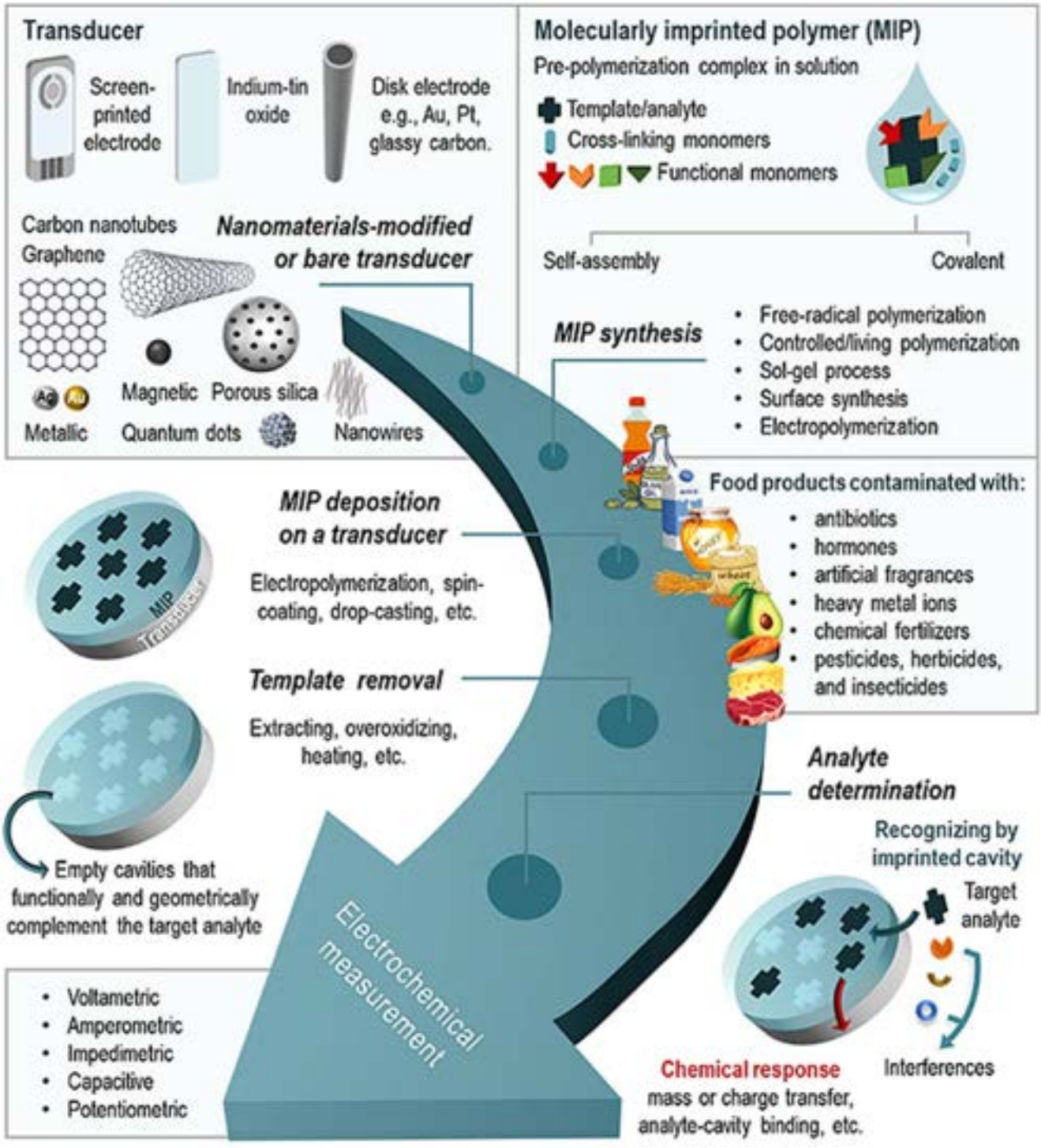

Figure 8. The fundamental concept of molecular imprinting, various electrochemical measurement techniques, and the strategies employed to detect electroactive, electroinactive, and catalytically active substances. Adapted with permission from the publisher[144].

MOF-based bio-bar codes to adsorb electroactive $Ru(NH_3)_6^{3+}$ on the electrode surface, which is then quantitatively measured. Demonstrating a broad linear detection range (0.005–150 ng ml^{-1}) and a low detection limit (2.6 pg ml^{-1}), alongside successful application in real milk samples, this dual-signal amplification strategy presents a novel approach for enhancing food safety monitoring.[145]

Enzymes are pivotal in designing bioelectrochemical sensors due to their substrate specificity and catalytic action, which facilitates the direct conversion of target analytes into electrochemically measurable products. Enzymatic bioelectrochemical sensors harness these properties to achieve high sensitivity and selectivity for specific food contaminants, such as pesticides and pathogens, or quality indicators like glucose or lactose concentration. Integrating enzymes onto sensor platforms often involves immobilization techniques that preserve enzyme activity while ensuring effective electron transfer between the enzyme and the electrode. Antibodies, or immunosensors, leverage the high specificity of antigen-antibody interactions, making them ideal for detecting specific proteins, allergens, or microbial pathogens in food samples. The binding of

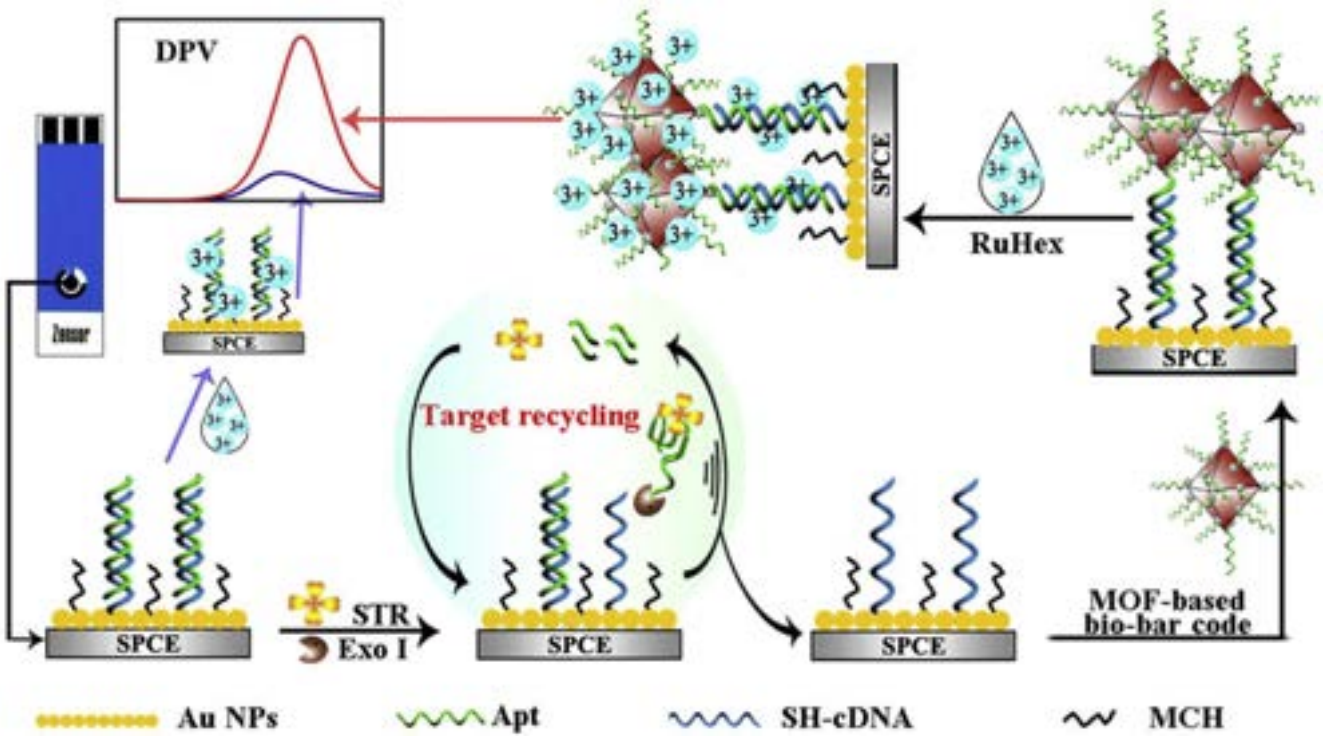

Figure 9. Sensitive detection of streptomycin in milk using a hybrid signal enhancement strategy of MOF-based bio-bar code and target recycling. Adapted with permission from the publisher[145].

the antigen (target molecule) to the antibody immobilized on the sensor's surface induces a change in the electrochemical signal, which can be quantified to determine the presence and concentration of the target. This approach is useful for identifying contamination that can lead to foodborne illnesses. Nucleic acids, including DNA and RNA, are employed in biosensors for their ability to hybridize specifically with complementary sequences. This capability is exploited in detecting genetically modified organisms (GMOs) in food or identifying specific bacterial or viral pathogens through their genetic material. Electrochemical sensors based on nucleic acids, or genosensors, can provide rapid, accurate, and sensitive detection, which is crucial for ensuring food safety and compliance with regulatory standards.[146]

Whole cells can serve as biorecognition elements in bioelectrochemical sensors, utilizing the metabolic activity of live cells to respond to the presence of specific analytes. This approach is beneficial for assessing the overall quality of food products, detecting spoilage, or monitoring the presence of toxic substances that affect cellular activity. Whole-cell biosensors can offer a more comprehensive insight into the effects of analytes on biological systems, reflecting their toxicity or nutritive value. The choice of biomaterial and its integration into the sensor platform are critical factors that determine the sensor's performance. The immobilization of biomaterials on the electrode surface must ensure their stability, activity, and accessibility to the target analytes while facilitating efficient electron transfer for electrochemical detection. Techniques such as adsorption, covalent bonding, entrapment in hydrogels or biocompatible polymers, and bioconjugation with nanoparticles are employed to achieve these goals.[147]

Challenges and Future Directions

Limitations of current electrochemical sensors and future directions.—Despite the significant strides made in electrochemical sensor technology for food safety and quality monitoring, several challenges remain. Intrinsic limitations, such as the selectivity and sensitivity of the sensors when dealing with complex food matrices, continue to pose difficulties. These matrices often contain a diverse range of interfering substances, leading to potential false positives or negatives due to matrix effects, which significantly impede the sensor's ability to accurately identify and quantify target analytes. Additionally, the long-term stability and reproducibility of electrochemical sensors are challenged by issues like the degradation of biorecognition elements and the fouling of electrode surfaces by sample components. Such factors can cause drift in sensor responses over time, necessitating frequent recalibration or replacement. Moreover, the detection limits of current sensors may not be adequate for trace-level contaminants that pose health risks even at extremely low concentrations.[148]

Looking ahead, future advancements in electrochemical sensor technology are expected to address these challenges. Innovations are likely to include the development of more robust biorecognition elements that are resistant to degradation and new materials that prevent electrode fouling. These advancements will enhance both the stability and longevity of sensors. Additionally, improvements in sensor design and manufacturing could lead to better selectivity and sensitivity, particularly for trace analytes in complex matrices. Integrating sensors with digital tools and advanced data analytics, such as machine learning algorithms, could further improve the accuracy and reliability of readings by compensating for matrix effects and sensor drift. Finally, greater emphasis on standardizing sensor designs and output data will facilitate the integration of these technologies into existing analytical frameworks and regulatory landscapes, making them more accessible and user-friendly for personnel. These future trends are pivotal for overcoming current limitations and will be crucial for the broader success and adoption of electrochemical sensors in food safety applications.

Emerging trends, technologies, and applications for electrochemical sensors.—In response to ongoing challenges, emerging trends and innovative technologies in the realm of electrochemical sensors are being explored and developed, promising significant advancements in food safety and quality monitoring. Nanotechnology and advanced materials science are leading the charge, introducing novel electrode materials and surface

modification strategies that significantly enhance electrochemical performance. This includes increased sensitivity and reduced susceptibility to matrix effects. Innovations in biotechnology have led to more robust and selective biorecognition elements, such as genetically engineered enzymes and synthetic antibodies, which maintain functionality across a wider range of environmental conditions and boast longer shelf lives. The integration of computational tools, including artificial intelligence (AI) and machine learning algorithms, with sensor data is revolutionizing the analysis and interpretation of complex datasets. This enables more accurate, reliable, and rapid detection of contaminants. Additionally, advances in microfluidics and lab-on-a-chip technologies drive the miniaturization and portability of sensors, enabling on-site testing and real-time monitoring without the need for specialized laboratory facilities.

The potential applications of these sensors extend well beyond their current capabilities, promising to redefine the landscape of monitoring systems. Innovative sensor technologies could enable comprehensive, real-time surveillance of food products throughout the entire supply chain, offering unprecedented control and transparency. The ability to detect a wider spectrum of contaminants, including newly emerging chemical and biological hazards, is crucial in addressing future food safety challenges. Furthermore, the integration of electrochemical sensors with Internet of Things (IoT) technologies could transform food safety management into a highly automated, interconnected system, allowing for continuous tracking of food quality and safety. This facilitates proactive interventions and enhances the sustainability and resilience of food production and distribution systems. These advancements not only promise to elevate the standards of food safety and public health protection but also significantly contribute to the global effort to ensure food security and sustainability in the face of growing population demands and environmental challenges.[149]

Conclusions

This review has thoroughly explored the advancements in electrochemical sensor technologies and their pivotal role in enhancing food safety and security. It detailed the operational principles of various sensors, including amperometric, potentiometric, conductometric, and impedimetric types, which are essential for detecting contaminants and assessing food quality. Key innovations such as the use of biorecognition elements like enzymes, antibodies, and nucleic acids have been emphasized for their critical roles in improving sensor specificity and sensitivity. Additionally, the integration of nanomaterials has markedly advanced sensor functionality by enhancing signal transduction and selectivity. The review not only covers technological advances but also addresses the challenges that persist, such as matrix effects, sensor stability, and the need for better sensitivity and selectivity. Future directions suggest promising developments through the use of advanced biomaterials and artificial intelligence to overcome these hurdles. The importance of regulatory frameworks and standardization in the adoption of new technologies within the food industry is also highlighted. Overall, this review points to a future where electrochemical sensors could revolutionize food safety monitoring by enabling more comprehensive and real-time detection across the food supply chain. The findings and insights presented are based on a rigorous survey of recent literature, emphasizing the necessity for ongoing research and a multidisciplinary approach to fully realize the potential of electrochemical sensors in global food security.

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