

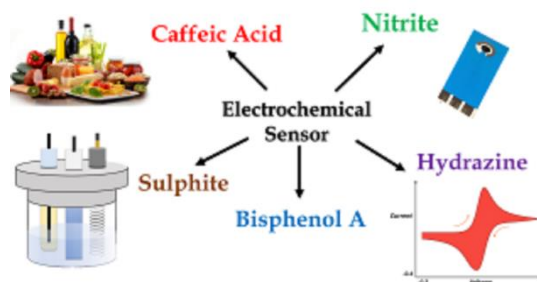
Electrochemical Sensors for Quality Control in the Food and Beverage Industry

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Abstract: Ensuring food safety and quality has become increasingly critical due to the rising complexity of the global food supply chain and the growing incidence of foodborne illnesses. This review aims to explore the potential of electrochemical sensors, enhanced with nanomaterials and artificial intelligence (AI), as efficient tools for detecting contaminants, additives, and adulterants in food and beverages. Traditional analytical techniques such as chromatography, spectroscopy, and titration though accurate, are often expensive, labour-intensive, and unsuitable for on-site or real-time analysis. In contrast, electrochemical sensors offer a rapid, low-cost, and portable alternative capable of providing accurate detection with minimal sample preparation. The incorporation of nanostructured materials like carbon-based nanomaterials, metal nanoparticles, and conductive polymers significantly boosts their sensitivity and selectivity by enhancing electron transfer and surface area. Furthermore, the integration of AI and machine learning (ML) techniques addresses major limitations of electrochemical sensors, including signal interference, overlapping analyte responses, and sensor drift. Algorithms such as SVM, CNNs, PCA, and PLSR enable multi-analyte detection, signal classification, and predictive maintenance, making real-time monitoring in complex food matrices feasible. Despite these advancements, challenges persist, including sensor fouling, matrix effects, lack of reproducibility, and difficulty in achieving regulatory compliance for industrial deployment. The review discusses these limitations in depth and outlines strategies to overcome them, such as adaptive calibration, surface modification, and AI-driven drift correction. Ultimately, this work highlights the transformative potential of AI-enhanced electrochemical sensors in modern food quality control and underscores the need for further development toward large-scale, industrial-ready applications.



Keywords: Electrochemical sensors, nanomaterials, food safety, food industry

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1. Introduction

Food is essential for human life because it provides energy, supports growth, and helps maintain health and body function. As a result, monitoring and controlling food quality and safety throughout the entire food supply chain is very important because poor food safety can have serious effects

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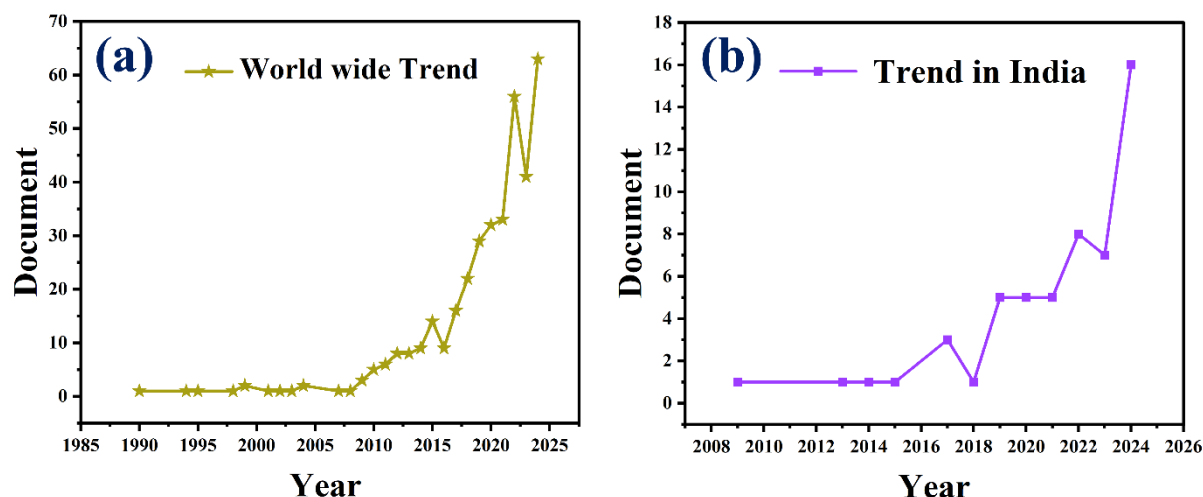
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on human health and well-being.¹ Hazardous materials including allergies, infections (such as bacteria, viruses, parasites, prions, etc.), toxic chemicals, or radioactive substances can all have an impact on food safety.² Regulatory



Scheme 1. The Scopus dataset of emerging research increment of electrochemical sensor for food and beverages (a) worldwide trend (b) trend in India

agencies such as the European Food Safety Authority (EFSA), the Chinese Food and Drug Administration (CFDA), and the United States Food and Drug Administration (USFDA) work to protect public health by ensuring food safety. These organizations set maximum limits for harmful substances in food. Despite these measures, according to a 2015 report by the World Health Organization (WHO), foodborne pathogens are still a major concern, causing over 600 million cases of illness and about 420,000 deaths worldwide each year.³ Numerous physical, chemical, and microbiological techniques have been employed to assess the composition and quality of food. The most often used techniques include fluorescence spectroscopy,⁴ chromatography,⁵ titration,⁶ electrophoresis,⁷ nuclear magnetic resonance,⁸ chemiluminescence,⁹ and surface plasmon resonance.¹⁰ Depending on the sample's properties and the kind of analysis needed, each of these approaches has unique benefits and features that make it more appropriate. Nevertheless, they frequently have serious disadvantages, such as the need for expensive equipment, time-consuming sample preparation, and highly skilled operators. Furthermore, their lack of portability and real-time sensing capabilities limits their use in dynamic environments like food manufacturing or retail.¹¹ Electrochemical sensors have emerged as a promising alternative, offering low cost, portability, ease of use, and rapid on-site detection. Advances in nanotechnology and device miniaturization have further improved their sensitivity, selectivity, and user-friendliness, positioning them as an attractive complement or replacement for traditional approaches. Research interest in this field has grown exponentially, as illustrated in **Scheme 1**. The trending graph was prepared using the Scopus database (<https://www.scopus.com>) with the search keywords "Electrochemical Sensors+ Food+ beverages". With the growing use of electrochemical sensors in the food and beverage industry, this review explores their basic principles, various sensing techniques, and how they are used to detect unwanted substances in food and drinks. It covers how electrochemical sensors work, including how they respond to chemical reactions by generating electrical signals. The review also looks at different types of electrochemical methods used to identify and measure impurities, contaminants and additives. These sensors play a key role in improving food safety by offering fast, accurate, and cost-effective ways to monitor food quality.

2. Knowledge Gaps and Emerging Challenges

In the last 20 years, the food industry has changed a lot, especially with the rise of global food trade through the Internet and online shopping. These changes have brought new problems, like making sure food is safe from harmful chemicals such as pesticides and animal medicines. Other issues include tracking where food comes from, identifying what's in it, checking for healthy plant ingredients, and spotting mistakes during production right away.¹² Current quality assessment of food and beverages mostly relies on physicochemical analyses (pH, °Brix, colour, texture),¹³ microbiological assays, sensory evaluation, and advanced instrumental techniques such as gas chromatography–mass spectrometry (GC-MS), high-performance liquid chromatography (HPLC), Fourier-transform infrared (FTIR) spectroscopy, and nuclear magnetic resonance (NMR) spectroscopy.^{14,15} However, these methods often cannot meet the growing demand for rapid, cost-effective, and field-deployable solutions. The need for quick, dependable, easy-to-use, and affordable techniques for quality and safety management has expanded due to the volume and complexity of food items.¹⁶ Unlike traditional tools, electrochemical sensors can solve many of today's challenges. They are small, low-cost, easy to use, and can give quick results right at the testing site, which is great for checking food safety. Thanks to new advances in nanotechnology and making devices smaller, these sensors are now even more accurate and easier to use, making them a good alternative to older methods.¹⁷

3. Basic and Fundamentals of Electrochemical Sensors

Electrochemical sensors have become increasingly important in the food and beverage industry due to their ability to quickly and accurately detect contaminants, impurities, and additives. An electrochemical sensor has four main parts: a receptor, a transducer, signal processing electronics, and a display unit. Electrochemical sensors, which use electrodes to detect chemical changes, work by measuring the electrical signals produced during oxidation or reduction reactions of the target analyte.^{18,19} These sensors often use a three-electrode system connected to a potentiostat and a display device.²⁰ Thanks to advances in nanotechnology and miniaturization, electrochemical sensors offer high sensitivity, portability, affordability, and fast response times, making them ideal for real-time, on-site food safety testing.²² Compared to traditional methods like chromatography, spectroscopy, and titration, electrochemical sensors are cheaper, more portable, and quicker.²¹⁻²³ However, traditional methods can still offer higher sensitivity and specificity, especially in complex samples.²⁴ Ongoing developments in materials and sensor design are

steadily improving the performance of electrochemical sensors, making them even more competitive for food safety and quality control applications.

3.1 Instrumentation

When studying the use of electrochemical sensors in food analysis, it is important to understand the basic components that make them work. Typically, these sensors consist of three main parts: the electrolyte solution, the electrodes, and the potentiostat has shown in **Figure 2a, 2b, 2c**. Each of these components plays a vital role in the sensor's performance, affecting properties such as response time, sensitivity, selectivity, and reliability. A clear and brief explanation of each

of these key parts is provided in the following sections shown in **Figure 1**.²⁵

3.2 Electrodes

Working Electrode (WE) is the primary site where the electrochemical reaction of interest occurs, as illustrated in **Figure 2d**. A potentiostat controls the voltage at the working electrode by referencing it against the potential of the reference electrode. The material used for the working electrode must remain chemically stable (i.e., redox-inert) over the applied potential range. The choice of working electrode material can be tailored to the specific requirements of the experiment, such as modifying the potential window or influencing the behavior

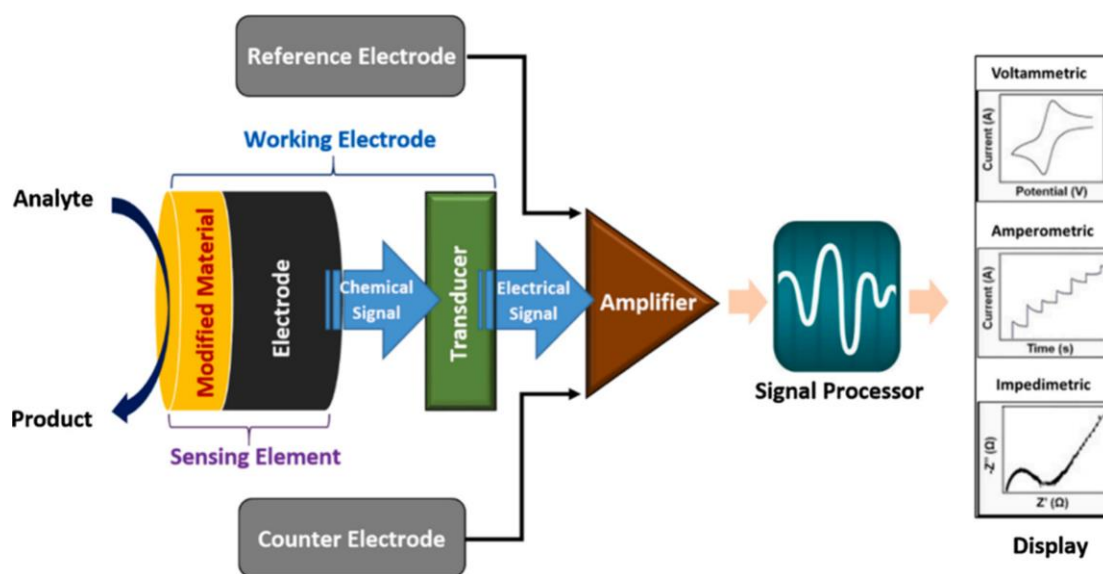


Figure 1. Shows the schematic diagram of electrochemical sensor. Reprinted with permission from ref²⁵ Copyright © 2022, American Chemical Society.



Figure 2. (a) Metrohm Autolab Potentiostat/Galvanostat (b) CHI Instrument Potentiostat (c) Biologic Potentiostat, (d) Working Electrode, (e) Graphite Counter Electrode, (f) Platinum Counter Electrode, (g) Ag/AgCl Reference Electrode (h) Hg/HgO Reference Electrode (i) Screen-Printed Electrode.

of adsorption of the target analyte. Furthermore, the surface of the electrode must be thoroughly cleaned and have a well-defined geometric area, as the electrochemical response directly depends on the reactions taking place at this interface.²⁶ The electroactive part of the working electrode is usually made from a conducting material shaped like a flat disc. This disc is placed into a rod-shaped support made of an inert material. The size of the electroactive disc is typically small, about 3 to 6 millimetres, to allow for good polarization during the reaction. In recent years, the use of certain materials like mercury in working electrodes has been reduced due to cost and environmental concerns. Instead, many researchers are now using various types of carbon-based materials, such as carbon paste, carbon fibre, pyrolytic graphite, and glassy carbon, or noble metals like gold and platinum.²⁷⁻³⁰

Reference Electrode (RE) consists of a standard potential which serves as a reference point to measure other electrode potentials. When reporting measurements, the potential is usually given as "vs" (versus) a specific reference electrode. Several commonly used reference electrodes maintain a stable potential, no matter what electrolyte is used. Some typical reference electrodes for experiments in water are the saturated calomel electrode (SCE) shown in **Figure 2h**, the standard hydrogen electrode (SHE), and the silver/silver chloride electrode (Ag/AgCl) shown in **Figure 2g**. Reference electrodes used in electrochemical measurements are often separated from the main electrolyte solution by a porous barrier (commonly called a frit) to prevent contamination and maintain a stable junction. To minimize errors from junction potentials, it is advisable to match the solvent and supporting electrolyte in the reference electrode with those used in the measurement system. In non-aqueous systems, silver/silver ion (Ag^+/Ag) reference electrodes are frequently employed. These typically consist of a silver wire immersed in a silver salt-containing solution, such as silver nitrate. As the potential of Ag^+/Ag electrodes can vary depending on the concentration of Ag^+ ions, the type of solvent, and the nature of the electrolyte, it is essential to specify the composition of the reference system used. Conversion tables are available to help adjust measurements from Ag^+/Ag references to other standard electrode systems, taking into account variations in solvent, salt, and concentration.³¹ To improve consistency across experiments, it is recommended to use an internal reference compound with a well-defined redox potential. Ferrocene is commonly used for this purpose due to its stable and reproducible electrochemical behavior. Researchers are encouraged to reference their results against the ferrocene/ferrocenium (Fc^+/Fc) redox couple, which is often assigned a potential of 0 V.^{32,33}

Counter Electrode (CE) completes the electrochemical circuit by enabling electron flow between itself and the Working Electrode (WE). When a voltage is applied to the WE, it initiates the redox reaction of the analyte, either reduction or oxidation, producing a measurable current. As this electron exchange occurs, the current generated by the electrochemical reaction is recorded. To ensure that the process at the counter electrode does not limit the overall cell performance, its surface area is typically made larger than that of the working electrode, as illustrated in **Figure 2e** and **2f**. Platinum wires or disks are frequently used due to their excellent conductivity and stability, though carbon-based materials are also viable alternatives.³⁴

Screen printed electrode (SPE), in recent times, SPE has drawn a lot of attention of the electrochemist due to their flexibility, cost effectiveness, adaptability, simplicity of manufacture and real time application, mainly for biosensors.³⁵ SPEs are a widely used type of printed electrode, fabricated by depositing conductive inks onto substrates such as paper, fabric, or plastic through a screen-printing process. They are created by screen-printing conductive inks onto materials such

as paper, fabrics, or plastics. While their design can be customized for specific applications, SPEs commonly integrate a counter electrode (CE), working electrode (WE), and reference electrode (RE) into a single compact platform, as illustrated in **Figure 2i**.

SPEs have several benefits over conventional electrodes, such as glassy carbon or platinum, including affordability, ease of mass manufacture, and disposability. They are perfect for biosensing and electrochemical tests because they offer great sensitivity, outstanding reproducibility, and flexibility. They are crucial in electrochemistry and biosensing because of their ease of customization for various uses.³⁶

3.3 Electrolyte

A good supporting electrolyte should have the following properties:

- It must dissolve easily in the chosen solvent.
- It should be chemically and electrochemically stable under the experimental conditions.

To enhance the solution's conductivity, a high concentration of supporting electrolyte is required. During electron transfer at the electrodes, the supporting electrolyte facilitates charge balance and maintains electrical neutrality by enabling ion movement within the system. The conductivity of the solution depends on how much of the salt is dissolved. If there isn't enough electrolyte to balance the charge, the solution will resist the flow of current. Therefore, using a high concentration of electrolyte is important for proper charge transfer.²⁶ The type of supporting electrolyte used mainly depends on the solvent. When water is the solvent, common supporting electrolytes include potassium chloride, potassium nitrate, sodium hydroxide, ammonium chloride, or hydrochloric acid. If pH control is needed, buffer systems like acetate, phosphate, or citrate are used. This flexibility in choosing the electrolyte allows researchers to set up different experimental conditions for various electrochemical studies and applications.³⁷

3.4 Electrochemical Methods

Electrochemical sensors can be developed using different electrochemical techniques, like voltammetry, chronoamperometry, impedance spectroscopy, and potentiometry. Among these, voltammetry is the prevalent technique due to its versatility in fabricating and evaluating electrochemical sensors. In voltammetric techniques, the electrical current is measured in relation to the applied potential, allowing for the identification and examination of a wide range of analytes. Various forms of voltammetry—such as differential pulse voltammetry (DPV), stripping voltammetry, square-wave voltammetry (SWV), and cyclic voltammetry (CV) are employed to detect and characterize different analytes. These techniques provide significant benefits in the assessment of electrochemical sensors and yield critical information about the properties and behaviour of the target analytes.³⁸ Cyclic voltammetry (CV), in particular, is a well-established technique for investigating the redox behavior and electrochemical characteristics of analytes. In a typical CV experiment, the potential is linearly swept back and forth between two limits while the resulting current is measured. This produces a cyclic voltammogram, which graphically represents the relationship between current and potential. The cyclic voltammogram provides important information about the kinetic (reaction speed) and thermodynamic (energy changes) properties of the analytes, making CV a powerful tool for understanding and analysing electrochemical reactions.³⁹

Differential pulse voltammetry (DPV) is another very useful method for developing electrochemical sensing. It is a highly sensitive type of voltammetry mainly used to detect very

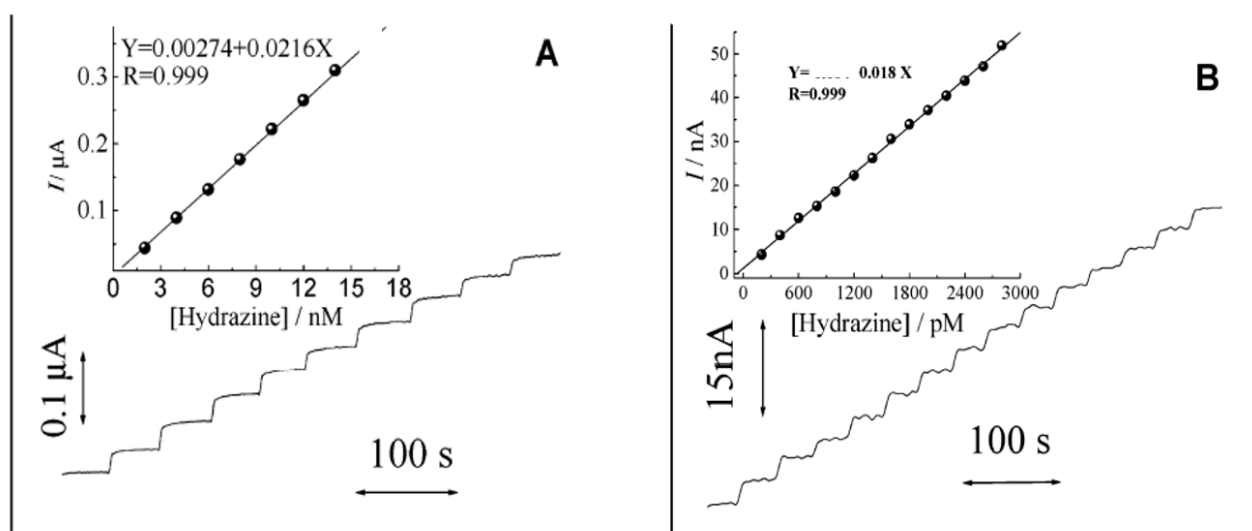


Figure 3. The amperometric signal of AuNP modified 3-(mercaptopropyl) trimethoxysilane based sensor between the range of (A) 2-18 nM hydrazine and (B) at lower concentration range of 200pM to 2000pM hydrazine. Reprinted with permission from ref⁵⁰ Copyright © 2019, American Chemical Society.

small amounts of analytes in samples. In DPV, small fixed pulses are applied on top of a steadily increasing voltage at the working electrode (WE). The current is recorded twice for each pulse, once immediately before and once after its application. The difference between these two current measurements is calculated and plotted against the corresponding potential to generate a differential pulse voltammogram characterized by distinct current peaks. The amplitude of each peak directly correlates with the concentration of the analyte, allowing for both qualitative and quantitative assessments. As DPV shows high responsivity and selectivity, it can efficiently detect the ultra-low concentrations of analytes in complex matrices. Data obtained from DPV are highly precise and reliable, enabling researchers to determine key sensor parameters such as the limit of detection (LOD) and linear range, both of which are essential for assessing sensor performance.³⁷ Over the past decade, DPV has been established as a most prevalent technique for developing a wide range of electrochemical sensors capable of detecting various analytes.⁴⁰

Amperometry is another very precise method often used to determine the linear range and limit of detection of electrochemical sensors. In this method, the analyte is added to the electrochemical cell at increasing concentration, and the alteration of the current is continuously measured at a constant potential bias. The resulting graph, called an amperometry, shows clear steps, with each step representing an increase in analyte concentration. Amperometry is usually considered more sensitive than differential pulse voltammetry (DPV) because it uses both diffusion and convection to move the analyte to the electrode surface. In contrast, DPV mainly depends only on diffusion for mass transport.⁴¹ Besides traditional electrochemical methods, several advanced strategies have been developed to make measurements more accurate and reliable. One important advancement is ratiometric electrochemical sensing. This technique improves accuracy by using two signals at the same time for internal calibration, while still following traditional electrochemical methods.^{42,43} Self-calibrating electrochemical sensors are another advanced approach. They use internal reference systems to automatically adjust for external factors like pH and temperature, ensuring stable and reliable results while still following traditional electrochemical methods.⁴⁴ Additionally, multimode electrochemical sensors combine several traditional techniques, such as impedance spectroscopy and

voltammetry, in a single device. This allows cross-checking of data and improves the accuracy of analyte detection.⁴⁵

These cutting-edge techniques, which expand on tried-and-true electrochemical techniques, provide notable gains in sensor performance precision, robustness, and dependability, especially in intricate analytical settings.

4. Electrochemical Sensing Techniques for Monitoring Food Additives and Contaminants

The increasing consumption of processed foods and beverages has driven the need for more stringent food safety and quality standards. To meet these standards, new strategies need to be developed. Electrochemical sensors could replace traditional methods, offer greater mobility and faster responses while eliminate the need for highly trained personnel. These sensors would be especially useful for detecting various compounds in different food types. Electrochemical sensing with nanomaterial sensors provides a prolific method for detecting food contaminations such as nitrite, hydrazine and common preservatives like sulphite, caffeic acid, and bisphenol A.

4.1 Hydrazine

Hydrazine and its related compounds are widely used in making products like foaming agents, insecticides, medicines, and chemicals that prevent rust.⁴⁶ They are also used in systems that heat water, such as boilers. Because hydrazine is used in industries like chemical production, making explosives, and aircraft fuel, it can be released into the environment.⁴⁷ Hydrazine can contaminate the human body through breathing, skin contact, or swallowing. It is highly toxic and can damage important organs like the liver, kidneys, and brain.⁴⁸

Due to the high toxicity and adverse effects of hydrazine on both human health and the environment, the use of precise and reliable analytical techniques for its detection is essential. Accurate monitoring is critical to ensure safety in industrial operations, safeguard the environment, and protect public health. Lu et al. developed hydrazine sensor based on a complexation-reduction strategy, where palladium (Pd) nanoparticles were coordinated with ethylenediamine

tetramethylenephosphonic acid (EDTMP) to form an EDTMP–Pd complex. To enhance the catalytic performance, multi-walled carbon nanotubes (MWNTs) were incorporated, yielding a Pd/MWNT composite that served as the active sensing material. Cyclic voltammetry (CV) analysis demonstrated enhanced electrocatalytic activity for hydrazine oxidation in an acidic electrolyte. DPV revealed a consistent increase in oxidation peak current with the stepwise addition of hydrazine. The sensor showed a wide linear detection range from 2.5 to 700.0 μM and a LOD of 1.0 μM .⁴⁹ Jena *et al.* developed a hydrazine sensor using nanoscale gold nanoparticles (AuNPs) embedded in a sol-gel matrix synthesized from 3-(mercaptopropyl) trimethoxysilane (MPTS). These AuNPs-modified electrodes function as nanoelectrode arrays, allowing for highly sensitive hydrazine detection at low operating potentials via voltammetric techniques. The sensor achieved excellent performance, demonstrating a LOD of 200 pM (S/N = 11). The electrocatalytic efficiency was strongly influenced by the density of AuNPs distributed within the silicate framework, shown in **Figure 3A** and **3B**. The nanostructured sensing interface exhibited good stability, making it well-suited for continuous hydrazine monitoring. Its high sensitivity was attributed to the collective behaviour of the nanoelectrode ensemble.⁵⁰ Kanan *et al.* introduced an electrochemical sensor constructed from multilayer graphene nanobelts (GNBs) for

hydrazine detection. The sensor demonstrated excellent sensitivity, achieving a response of $0.08 \mu\text{A} \mu\text{M}^{-1} \text{cm}^{-2}$, with a wide linear detection range spanning from 10 μM –1.36 mM. The sensor's cross sensitivity was further examined in presence of common interfering substances such as uric acid, ascorbic acid, lactic acid and glucose. The results demonstrated excellent selectivity toward hydrazine, with minimal interference from these species. This highlights the potential of the GNB-based platform for reliable and accurate hydrazine detection in complex sample matrices.⁵¹

4.2 Bisphenol A

Bisphenol A (BPA) is prevalently employed as a monomer in the production of high-performance polymers such as polycarbonate plastics and epoxy resins. Owing to their mechanical strength and chemical resistance, these polymers are extensively used in the manufacture of packaging materials and containers.^{52–54} However, BPA is also classified as an endocrine-disrupting chemical (EDC), with studies indicating that it may lead to significant harmful effects on biological systems and ecosystems. Exposure to certain concentrations of BPA can interfere with normal hormonal regulation in humans, potentially leading to hormonal imbalances and the onset of various endocrine-related disorders.^{55–58}

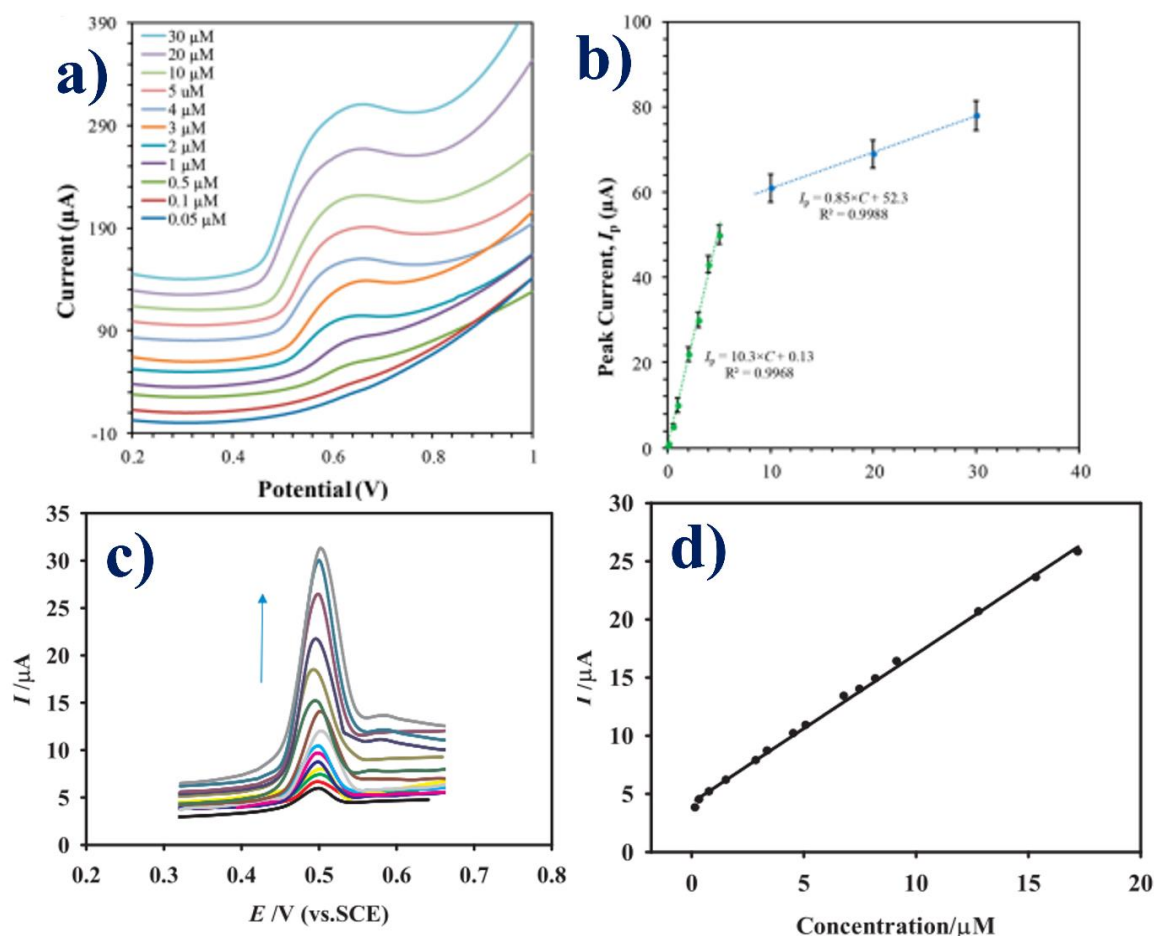


Figure 4. (a) LSV graph represent the data for varying the concentration of Bisphenol A by using GO-MWCNT- β CD modified screen-printed electrode (SPE) in 0.01 M phosphate buffer solution (PBS, pH 7.4) (b) Representation the calibration plot for concentration variation of BPA Reprinted with permission from ref⁵⁹ Copyright © 2020, American Chemical Society (c) DPV graph shows the concentration variation (0.18 to 18 μM) of BPA for in pH 7.0 PBS. (d) Shows the linear relationship of peak current and concentrations. Reprinted with permission from ref⁶¹ Copyright © 2019 Elsevier Ltd. All rights reserved.

Therefore, it is very important to develop a sensitive and reliable methods to detect BPA in environmental samples, especially methods that can accurately measure BPA even when many other substances are present. Alam *et al.* developed a low-cost and sensitive electrochemical sensor to detect BPA in water using a combination of graphene oxide, β -cyclodextrin, and multiwalled carbon nanotubes (MWCNTs). The large surface area to volume ratio of the GO and MWCNTs and the ability of β -cyclodextrin to trap BPA enable the prepared sensors to efficiently detect trace amounts of BPA in water. The BPA detection is based on a diffusion-controlled oxidation process involving equal numbers of electrons and protons. The sensor showed a clear and accurate response in two concentration ranges: 0.05–5 μM and 5–30 μM , with LOD of 6 nM BPA, as shown in **figure 4a** and **4b**. It remained stable and consistent for up to a month, worked well even in the presence of other substances, and gave excellent results when tested with real water samples.⁵⁹

In other work, a novel electrochemical sensor for detecting BPA was developed by modifying a GCE with a nanocomposite consisting of MWCNTs and AuNPs, as demonstrated by Messaoud *et al.* The sensor characterization was performed using DPV and electrochemical impedance spectroscopy (EIS). Various amounts of MWCNTs and AuNP layers were optimized, along with pH effects, to enhance performance. Under optimized conditions, the sensor exhibited

a linear response to BPA concentrations ranging from 0.01 μM to 0.7 μM , with an impressive LOD of 4 nM, among the lowest reported values. The sensor also demonstrated excellent repeatability, reproducibility, and long-term stability, surpassing the performance of comparable BPA sensors previously reported.⁶⁰

In another study, Mo *et al.* designed a highly sensitive electrochemical sensor for BPA detection using a nanocomposite composed of gold-palladium (AuPd) nanoparticles anchored on carboxyl-functionalized MWCNTs. The MWCNTs acted as a conductive scaffold to support efficient electron transfer, while poly (diallyldimethylammonium chloride) (PDDA) was employed as a dispersing agent to minimize MWCNT aggregation via electrostatic repulsion and van der Waals interactions. Despite the low content of AuPd, the MWCNT-PDDA-AuPd nanocomposite exhibited superior electrocatalytic activity toward BPA oxidation compared to its monometallic counterparts and MWCNT-PDDA alone. The sensor exhibited a linear response trend to BPA concentrations ranging from 0.18 to 18 μM , with a detection LOD of 60 nM, as shown in **Figures 4c** and **4d**. In addition, it demonstrated excellent sensitivity, stability, and reproducibility, indicating its suitability for BPA sensing in real samples, i.e. milk and water. These findings emphasise the potential of the MWCNT/PDDA/AuPd nanocomposite for applications in food safety control and environmental monitoring.⁶¹

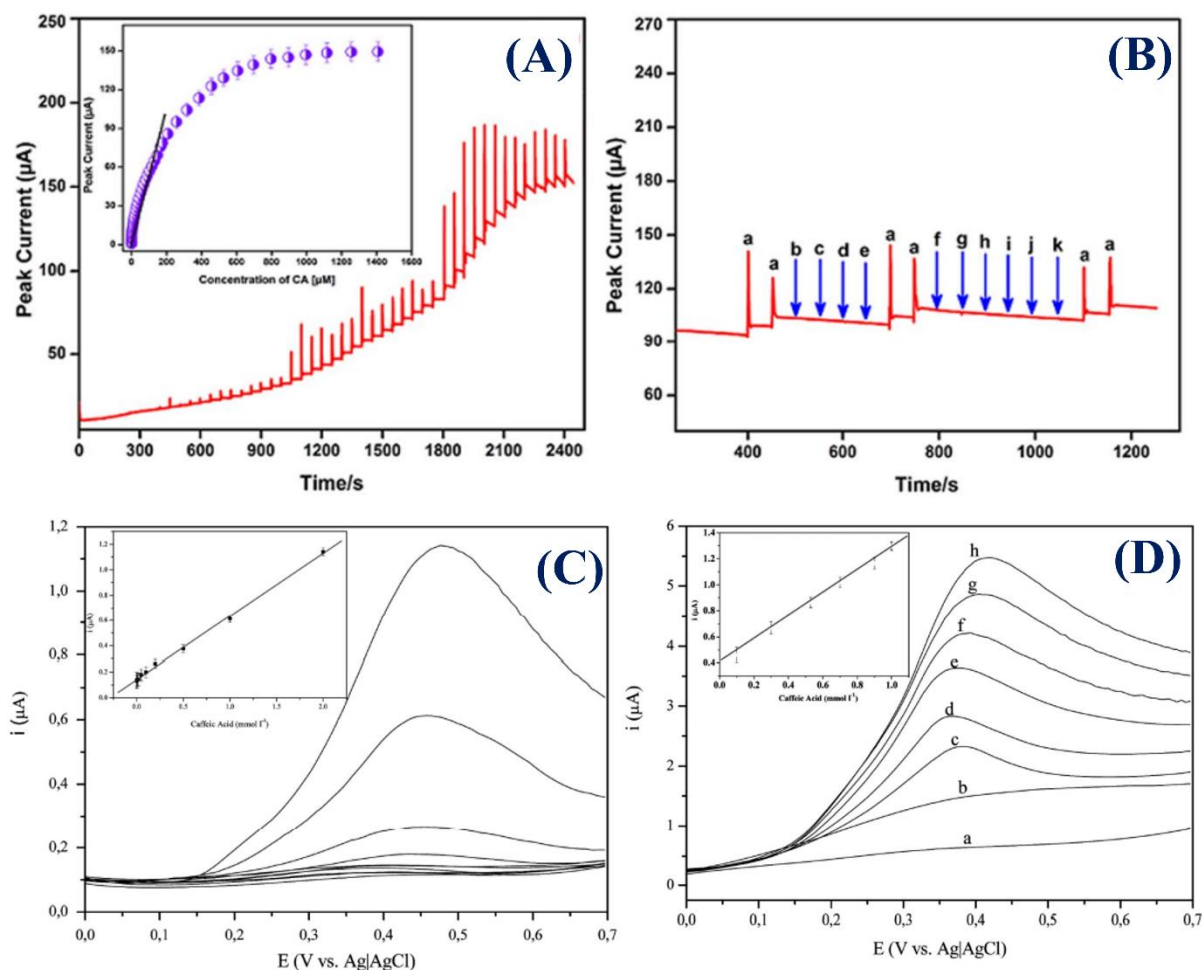


Figure 5. (A) shows amperometric responses (B) represents the amperometric data of the same electrode under the same conditions, but for 50 μM of CA in the presence of other substances that could interfere all added at concentrations 50 times higher than CA. Reprinted with from ref.⁶⁹ published in 2017 by Nature Publishing Group, under the terms of the Creative Commons CC BY license. (C) The DPV variation of concentration and (D) shows the DPV of interference. Reprinted with permission from ref⁷⁰ Copyright© 2012, American Chemical Society.

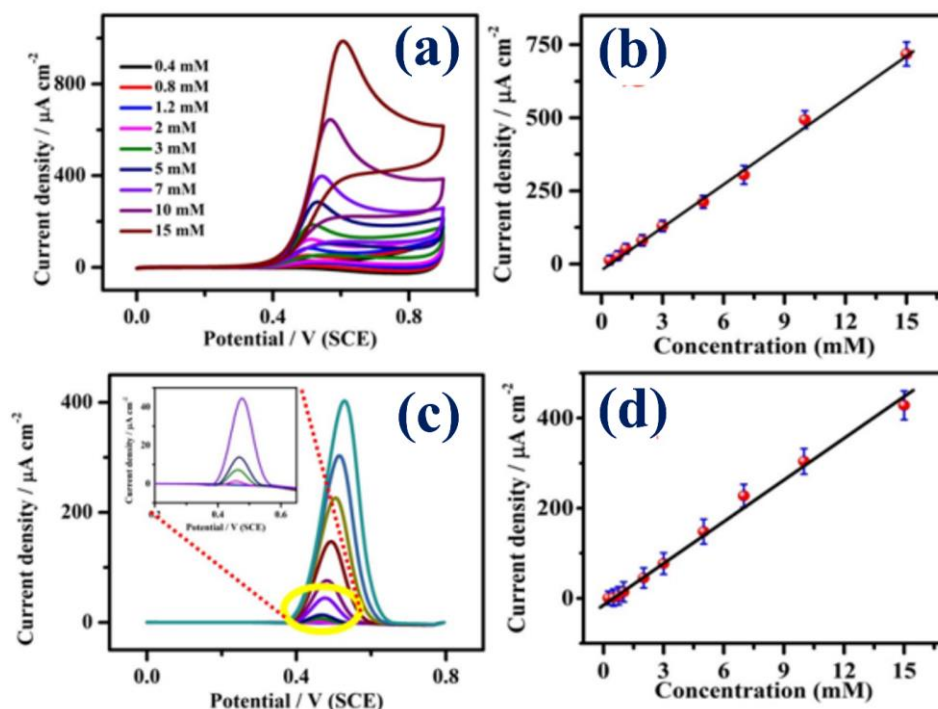


Figure 6. (a) CV of CuO/GCE in the presence of various concentrations of SO_3^{2-} in 0.1 M PBS solution; (b) shows the corresponding calibration curve ($n=3$). (c) Differential pulse voltammogram DPV data shows the concentration variation (0.2 to 15 mM) of SO_3^{2-} in 0.1 M PBS solution by using CuO modified electrode. The image in the insert is the DPV for the low concentration region. (d) Linear relationship of current density to the concentration ($n=3$). Reprinted from ref⁷³, published in 2017 by Nature Publishing Group, under the terms of the Creative Commons CC BY license.

4.3 Caffeic Acid

Phenolic compounds are now commonly used to add flavour and improve stability in plant-based non-alcoholic and alcoholic beverages, i.e. wine, beer, and fruit juices.^{62,63} One important compound in this group is 3,4-dihydroxycinnamic acid, also known as caffeic acid. Phenolic acids like caffeic acid are widely used in medicine for their beneficial effects, including anti-inflammatory, antibacterial, antioxidant, immune-boosting, and anticancer activities.⁶⁴⁻⁶⁷ It is very important to detect trace amounts of caffeic acid in the food and beverage samples, and the electrochemical technique is one of the most reliable, accurate, and cost-effective for detecting caffeic acid. In recent years, many electrochemical developments have been made to detect caffeic acid. Parasuraman *et al.* developed a non-enzymatic electrochemical sensor using a $\text{Bi}_2\text{S}_3/\text{CNF}/\text{GCE}$ nanocomposite electrode for detecting caffeic acid (CA). The sensor exhibited excellent performance, featuring a wide linear detection range of 0.1–500 mM CA, a LOD of 108 nM, and high sensitivity of $2.56 \mu\text{A } \mu\text{M}^{-1} \text{ cm}^{-2}$. As the sensor also exhibited good sensitivity, selectivity, reproducibility, and stability, it was successfully applied to the detection of CA in real samples like apple and grape juice. This indicates its strong potential for applications in the food and healthcare industry.⁶⁸ In another study, Karthik *et al.* developed a rod-shaped strontium vanadate (SrV_2O_6)/GCE-based sensor to create an electrochemical sensor for detecting CA. The sensor gave a strong and stable current response to CA, with excellent selectivity, a large detection ranges of 0.01–207 μM CA, a LOD of 4 nM, and high sensitivity ($2.064 \mu\text{A } \mu\text{M}^{-1} \text{ cm}^{-2}$), as illustrated in **Figure 5A** and **5B**.⁶⁹

Di Carlo *et al.* developed an eco-friendly electrochemical sensor for the detection of CA using colloidal AuNPs stabilized in a chitosan matrix. The AuNPs were synthesized by reducing gold ions (Au^{3+} to Au^0) in a water-based solution containing chitosan and various organic acids. Chitosan, a natural, biodegradable polymer rich in amino and hydroxyl groups,

helped both form and stabilize the AuNPs in a single step. Due to chitosan's strong film-forming ability, the resulting AuNP–chitosan mixture was used to create hybrid nanocomposite films that combined the high conductivity of gold nanoparticles with the functional properties of chitosan. These AuNP–chitosan films were used to construct an electrochemical sensor that was highly sensitive and selective for caffeic acid, an antioxidant known for its health benefits. The sensor demonstrated a large detection range of CA between 50 nM–2 mM and having a LOD of 25 nM. Importantly, it demonstrated excellent selectivity for caffeic acid, with no interference from similar compounds like catechin or ascorbic acid shown in **Figure 5C** and **5D**.⁷⁰

4.4 Sulphite

Sulphite (SO_3^{2-}) acts as an antimicrobial agent and is prevalently used as a preservative in packaged food.⁷¹ Sulphite is used in food and wine to enhance appearance and preserve quality. According to the U.S. FDA, the recommended limit for sulphite in food is less than 10 mg/kg, and in liquids, less than 10 mg/L.⁷² However, excessive intake of sulphite can cause adverse health effects such as asthma and can alter the taste, smell. In certain cases, sulphites are still used in wine and various food products due to the absence of effective alternatives. Moreover, sulphites act as precursors to acid rain, which can lead to the acidification of water bodies and soil, and cause damage to vegetation, crops, buildings, and historic monuments. Accurate detection of trace levels of sulphite in food, surface water, drinking water, and other sources is essential. Electrochemical techniques offer a highly accurate, precise, and cost-effective method for sulphite detection. The following is an overview of recent advancements in sulphite sensor development. A simple one-step chemical synthesis method was used to prepare three copper-based oxides: Cu_2O , CuO , and $\text{CuNa}_2(\text{OH})_4$. Sudha *et al.* investigated the electrochemical sensing of sulphite (SO_3^{2-}) using electrodes modified with these materials. Among the three, CuO exhibited the highest electrocatalytic activity for sulphite oxidation. A

linear relationship between the oxidation peak current and sulphite concentration was observed in the range of 0.2 to 15 mM under optimized conditions shown in **Figure 6 (a-d)**.^{73a}

The sensor showed a sensitivity of $48.5 \mu\text{A cm}^{-2} \text{ mM}^{-1}$ and a LOD of $1.8 \mu\text{M SO}_3^{2-}$. A CuO-modified electrode was employed for sulphite detection in commercial wine samples, demonstrating its practical utility. Dadamos *et al.*^{73b} introduced an electrochemical sensing strategy using a platinum electrode coated with a nanostructured copper salen polymer (salen = N,N'-ethylenebis(salicylideneiminato)) by electropolymerization method, using a solution of 0.1 mol L^{-1} tetrabutylammonium perchlorate in acetonitrile. The prepared sensor was characterized through cyclic voltammetry across the potential range of 0 to 1.4 V vs. SCE. After conditioning the electrode in 0.50 mol L^{-1} KCl, the surface concentration was found to be $2.2 \times 10^{-9} \text{ mol cm}^{-2}$. While sulphite oxidation on bare platinum typically occurs at approximately +0.9 V vs. SCE, the modified electrode lowered the oxidation potential to around +0.45 V, reducing interference from other electroactive species. Chronoamperometric measurements performed at +0.45 V revealed a linear response to sulphite concentrations within the range of 4.0 to $69 \mu\text{mol L}^{-1}$, with a LOD of $1.2 \times 10^{-6} \text{ mol L}^{-1}$.

In another study, Silva *et al.* employed a square-wave voltammetric technique for quantifying sulphite concentration in commercial beverages. A MWCNTs functionalized carbon paste electrode was used as the sensing platform. Under optimized conditions, the sensor exhibited a linear sulphite detection range of 1.6 – 32 mg L^{-1} (equivalent to 25 – $500 \mu\text{mol L}^{-1}$), with a LOD of 1.0 mg L^{-1} ($16 \mu\text{mol L}^{-1}$).⁷⁴

4.5 Nitrite

The excessive use of nitrite as a chemical fertilizer in agriculture and as a food additive has led to significant negative impacts on both environmental ecosystems and public health over recent decades.^{75–78} Inhalation of even minor amounts of nitrite can result in severe toxicity, while prolonged exposure has been linked to carcinogenic effects.⁷⁹ Consequently, the accurate and rapid quantification of nitrite has become a subject of considerable interest. Current analytical methods for nitrite detection include chromatography, spectrophotometry, capillary electrophoresis, and electrochemical techniques.⁸⁰ Among these, electrochemical sensing is particularly favoured due to its high sensitivity, low cost, operational simplicity, rapid response, portability, and suitability for on-site analysis.^{76–78,81,82} In their study, Zhu and colleagues developed an air-annealed carbon

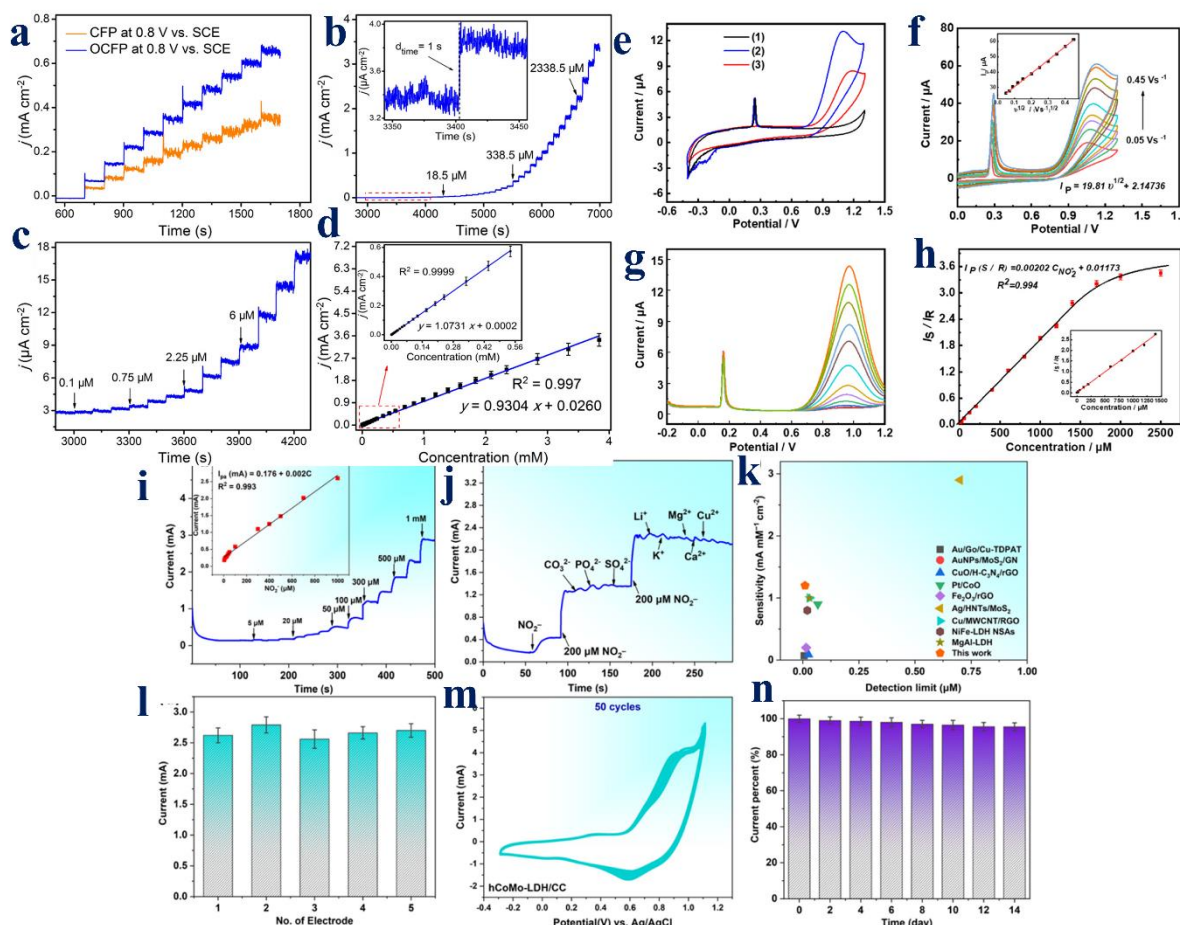


Figure 7. (a) Amperometric data of the CFP and OCFP for the addition of 0.0625 mM nitrite. (b,c) Amperometric data of OCFP in the presence of 0.1 to $3838.5 \mu\text{M}$ of nitrite and the inset shows the response time. (d) Amperometry data corresponding to the concentration of nitrite. Reprinted with permission taken from ref ⁸³ Copyright © 2019 American Chemical Society. (e) CV data (1) with 0.4 mM NaNO_2 , (2) without 0.4 mM NaNO_2 solution by using AgNC/NCS electrode and (3) SPE with the same concentration of NaNO_2 in the 0.1 M PBS . (f) CV of different scan rate and inset shows the linear relationship of peak current and scan rate. (g) DPV of sodium nitrite (1.12 to $1400 \mu\text{M}$) by using the AgNC/NCS electrode in 0.1 M PBS . (h) Calibration curve for the current response and the NaNO_2 concentration. Reprinted with permission taken from ref ⁴⁴ Copyright © 2022 American Chemical Society. (i) Amperometry for the successive addition of nitrite at a potential 0.90 V by using hCoMo-LDH/CC electrode and the inset shows the linear relation of current response and concentration. (j) Amperometry with 0.2 mM nitrite and 2 mM of interfering ions. (k) Comparison of the literature of various active electrodes compared to hCoMo-LDH/CC electrodes. (l) The reproducibility graphs in the presence of 1 mM NaNO_2 . (m) CV repeatability over 50 cycles at 50 mV s^{-1} scan rate. (n) The stability monitoring of the electrode in a gap of 2 days for 14 days in presence of 1 mM NaNO_2 . Reprinted with permission taken from ref ⁸⁴ Copyright © 2021, American Chemical Society.

fibre paper (CFP), which was used for electrochemical nitrite sensing. The air-annealing process enhances the CFP by introducing surface defects, increasing oxygen-containing functional groups, improving surface roughness, and enhancing wettability, thereby resulting in the oxidized CFP (OCFP) exhibiting superior nitrite sensing performance, including an ultra-low LOD of 0.07 μM , a wide linear detection ranges from 0.1- 3838.5 μM , a fast response time of just 1 second, and a high sensitivity of 930.4 $\mu\text{A mM}^{-1} \text{cm}^{-2}$. These results are comparable to or better than many advanced nitrite sensors based on noble or transition metals shown in **Figure 7(a-d)**.⁸³ In another work, Yin and coworkers developed a method called in situ confinement polymerization to create silver nanoclusters (AgNCs) that are evenly distributed on nitrogen-doped carbon sheets (NCS). They used N-vinyl functionalized imidazolium ionic liquids as both stabilizers and carbon sources. The resulting AgNC@NCS material showed excellent electrochemical and catalytic performance because of its well-controlled structure, layered carbon support, and the confinement effect that helps maintain stability and activity. This material was then used to make a printed electrode that also served as an internal reference for accurate, ratiometric detection. Nitrite was chosen as the target analyte to test the sensor, which showed outstanding results: a wide linear detection ranges from 1.12 to 1400 μM , a low detection limit of 0.38 μM , good stability, and strong resistance to interference from other substances shown in **Figure 7(e-h)**.⁴⁴ Chen *et al.* developed a cobalt-based metal-organic framework (ZIF-67) as a starting material and used a template-sacrificing method to create hollow cobalt-molybdenum layered double hydroxide (hCoMo-LDH) nanopolyhedra. These hollow structures were used to build a self-supporting electrode on carbon cloth (hCoMo-LDH/CC) for electrochemical sensing. When tested for nitrite detection, the electrode showed excellent performance, with an extremely low LOD of 0.01 μM , a broad linear detection ranges from 1 to 1500 μM , and a high sensitivity of 1020 $\mu\text{A mM}^{-1} \text{cm}^{-2}$ shown in **Figure 7(i-n)**.⁸⁴

5. Artificial Intelligence and Machine Learning in Electrochemical Food Quality Monitoring

Combining electrochemical sensing technologies with artificial intelligence (AI) and machine learning (ML) has become a game-changing method for food and beverage quality management. These sophisticated computational techniques provide real-time, precise, and predictive quality assessment by addressing significant drawbacks of traditional electrochemical sensors, such as low selectivity, signal interference, and sensor drift.⁸⁵ Complex current-potential responses are frequently produced by electrochemical sensors and are impacted by matrix effects, overlapping redox peaks, and ambient noise. In complex food matrices like milk, wine, or fruit juices, target analytes may be difficult to separate from interferents using conventional data interpretation. Robust signal deconvolution and classification are provided by AI and ML methods, such as Support Vector Machines (SVM).⁸⁶

Random Forest,⁸⁷ k-Nearest Neighbours (k-NN),⁸⁸ and Deep Learning architectures (e.g., Convolutional Neural Networks, CNNs).⁸⁹ These algorithms allow precise multi-analyte detection without requiring a lot of sample preprocessing by identifying subtle patterns in voltammetric or amperometric profiles. For instance, CNN-assisted voltammetry has overcome the selectivity limits of traditional sensors to successfully distinguish between structurally identical phenolic chemicals in beverages. Monitoring several pollutants, additives, or adulterants at once is frequently necessary to ensure complete food safety. Traditional single-analyte electrochemical sensors are insufficient for high-throughput industrial quality control. Unique fingerprints can be extracted from overlapping signals produced by sensor arrays

using machine learning (ML)-based multivariate calibration models like Principal Component Analysis (PCA) and Partial Least Squares Regression (PLSR).^{90,91} This approach facilitates simultaneous quantification of pesticides, heavy metals, and phenolic compounds in complex matrices, substantially improving detection efficiency and reducing false positives or negatives. Sensor drift and surface fouling are significant industrial problems that raise maintenance needs in continuous production lines and jeopardize reproducibility.⁹² Predictive maintenance algorithms with AI capabilities can forecast sensor end-of-life, suggest recalibration, and spot early drift tendencies.⁹³ Furthermore, adaptive machine learning models have the ability to automatically correct for slow signal deterioration, increasing sensor lifetime and guaranteeing continuous, highly accurate quality control.

6. Limitation and challenges of electrochemical sensors and ways of overcome

The electrochemical sensors have the number of limitations and challenges. Electrochemical signals of multiple analytes often overlap, causing interference from similar compounds (e.g., phenolic compounds, ascorbic acid, and uric acid in beverages). Food matrices often contain proteins, fats, sugars, and polyphenols that adsorb on electrode surfaces. This leads to passivation of the electrode, decreasing sensitivity over time. Sensor response may degrade due to temperature variations, pH fluctuations, and storage conditions. Reproducibility is often a challenge for portable, disposable sensors. Real food and beverage samples contain multiple co-existing compounds that can cause matrix effects, masking the actual analyte signal. Enzyme-based electrochemical biosensors may lose activity due to denaturation, microbial contamination, or dehydration. Frequent calibration is needed to maintain accuracy. Lack of universal reference standards complicates sensor deployment in industrial QC processes. When included into industrial QC pipelines, electrochemical sensors encounter particular challenges: Different substances included in food products including milk, wine, and sauces might produce cross-reactivity or conceal signals. Highly precise, repeatable, and validated analytical results are required by agencies such as the FDA, EFSA, and FSSAI. For some pollutants, electrochemical sensors frequently have trouble reliably reaching ppm or ppb detection limits. Sensors used in online quality monitoring must be able to function continuously, require little maintenance, and tolerate changes in temperature and humidity. Real-time monitoring, which is essential for beverages like beer or dairy products, may be interfered with by frequent cleaning or sensor replacement. Inaccurate readings could result in missing contamination or needless product rejection because of interference from naturally occurring substances. Electrochemical sensors face several limitations in food quality monitoring, such as signal overlap, electrode fouling, low stability, and interference from complex food matrices. To overcome these challenges, various strategies have been developed. Selectivity can be improved using molecularly imprinted polymers, nanocomposites, and multi-modal sensing techniques, which help distinguish between similar compounds. Electrode fouling caused by fats, proteins, and sugars can be minimized through anti-fouling coatings, protective membranes, and sample pretreatment. Stability and sensor lifespan can be enhanced by using robust materials, replacing enzymes with non-enzymatic elements, and encapsulating biological components. Reproducibility and standardization are improved through microfabrication, internal standards, and universal testing protocols. Detection limits are lowered using signal amplification, preconcentration techniques, and multivariate data analysis. Integration with artificial intelligence and machine learning enables advanced signal processing, drift correction, and predictive maintenance, improving sensor accuracy and lifetime. For industrial use,

sensors are being designed with rugged packaging, wireless connectivity, and automated calibration, making them suitable for real-time, continuous food quality monitoring across production and supply chains.

7. Future Scope

Electrochemical biosensors are expected to improve a lot in the coming years, especially in the area of food safety. **Table 1** compares various nanomaterial-based sensors reviewed in this work. In the future, these sensors could be built into small, portable, or even wearable devices to check food for harmful substances right on the spot, this would be really useful for both food companies and regular consumers. Scientists are also working on new materials like smart nanocomposites and special metal-based structures that can make these sensors even faster, more accurate, and longer-lasting. Another exciting direction is using machine learning and data tools with these sensors to help understand results better and even predict food contamination before it becomes a problem. There's also potential to shrink these devices down into tiny chips that can test for many harmful chemicals at once, even in complicated food samples. For these technologies to be used widely, they'll need to be approved by food safety authorities and made available on the market. Overall, this field is moving toward a future where checking food safety is easier, quicker, and more reliable for everyone.

8. Conclusion

Electrochemical and nanomaterial-based sensors represent a promising advancement in the detection of food contaminants and additives, offering significant improvements over conventional analytical methods. Their enhanced sensitivity and selectivity stem from the use of nanostructured materials such as carbon-based nanomaterials, metal nanoparticles, and various nanocomposites. These materials, due to their high surface area, unique morphologies, and ability to interface with conductive polymers, contribute to faster

electron transfer and more efficient signal transduction, resulting in superior analytical performance. In particular, electrochemical immunosensors incorporating advanced nanomaterials have demonstrated excellent specificity and ultra-low detection limits, making them ideal for detecting trace levels of harmful substances in complex food matrices. Despite their promising performance in laboratory settings, the transition of these sensors to practical, real-world food industry applications remains limited. A major hurdle lies in the lack of robust validation under actual field conditions. Issues such as sensor stability over time, reproducibility of results, long-term performance, and the potential toxicity of nanomaterials need to be rigorously addressed. Moreover, regulatory compliance and standardization pose additional barriers, as most reported sensors have yet to meet the strict quality control requirements demanded for commercial deployment.

Although extensive research has led to the development of numerous electrochemical and nanomaterial-based sensors, very few have reached the stage of market availability. To bridge this gap, large-scale field trials, inter-laboratory validations, and comprehensive reliability studies are essential. Looking ahead, future developments in this field may involve the integration of sensors with digital platforms such as smartphones or tablets, paving the way for portable, user-friendly smart sensing systems capable of real-time monitoring of food safety and quality. These innovations could transform food safety assurance practices, making them faster, more efficient, and accessible across the supply chain.

Author Contribution Declaration

Suman Mondal: Conceptualization; Literature Review; Writing-original draft; review & editing. **Snehangshu Paine:** Literature Review; Writing-original draft; review & editing. **Kalisadhan Mukherjee:** Supervision; Conceptualization; Writing- review & editing.

Table 1. List of different electrochemical sensors and the techniques used for detecting various target analytes.

Nanomaterials	Linear range	LOD	Target analytes	Electrochemical techniques	Ref
PSS-graphene	3.0 to 300.0 μM	1 μM	Hydrazine	CA	94
PEDOP/MWCNTs-Pd/GCE	0.1 - 5000.0 μM	0.08 μM	Hydrazine	CA	95
Au/ SW nanohorns	0.005- 3.345 mM	1.1 μM	Hydrazine	CA	96
Pd/MWCNTs	2.5 - 700.0 μM	1 μM	Hydrazine	DPV	49
AuNPs/CNTs-ErGO/GCE	0.3 to 319.0 μM	0.065 μM	Hydrazine	CA	97
Pd/CILE Hydrazine	5.0 - 800.0 μM	0.82 μM	Hydrazine	SWV	98
ZnO/CNTs	0.7 - 550.0 μM	9.0 nM	Hydrazine	SWV	99
Fe ₃ O ₄ -Si ₄ Pic+Cl-/Au-NPs-Si ₄ Pic+Cl-/GCE	20.0 - 1400.0 nM	7.0 nm	Bisphenol A	DPV	100
Au-Pd NPs/GNs/GCE	0.05 to 10.0 μM	8.0 nm	Bisphenol A	DPV	101
Cu ₂ O/rGO/GCE	0.1 to 80.0 μM	0.085 μM	Bisphenol A	DPV	102
AuNP/Gr nanosheets/GCE	0.5 - 50.0 μM	0.05 μM	Caffeic Acid	DPV	103
PEDOT/Pt electrode	0.01 - 6500.0 μM	0.03 μM	Caffeic Acid	DPV	104
CRGO/GCE	0.01 - 800.0 μM	0.002 μM	Caffeic Acid	DPV-CA	105
Nafion/ERGO/GCE	0.1 - 10.0 μM	0.091 μM	Caffeic Acid	SW-AdSV	106
Molecularly imprinted Siloxanes	0.5 - 60.0 μM	0.15 μM	Caffeic Acid	DPV	107
Au-PEDOT/rGO/GCE	0.01 - 46.0 μM	0.004 μM	Caffeic Acid	DPV	108
Pb/GCE	0.01 - 0.5 μM	0.004 μM	Caffeic Acid	DPV	109
Activated GCE	0.1 - 1.0 μM	0.068 μM	Caffeic Acid	DPV	110
Glassy Polymeric carbon	0.97 - 11.0 μM	0.29 μM	Caffeic Acid	DPV	111
Green bean/Chitin/CPE	0.97 - 11.0 μM	0.29 μM	Caffeic Acid	DPV	112
Sulfite oxidase/GCE	200.0-2800.0 μM	20 μM	Sulphite	CV	113
BF/IL/Graphene-nanosheets paste	0.05 - 50.0 μM	0.02 μM	Sulphite	SWV	114
MWCNT/Carbon paste electrode	25.0 - 500.0 μM	16 μM	Sulphite	SWV	74
FeHCF/GCE	100.0-2380.0 μM	80 μM	Sulphite	CV	115
nanostructured copper/Pt	4.0 - 69.0 μM	1.2 μM	Sulphite	CA	116
Chitosan-ferrocene/MWCNT/GCE	5.0 - 1500.0 μM	2.8 μM	Sulphite	CA	117
SOx/Fe ₃ O ₄ @GNPs/Au	0.50 - 1000.0 μM	0.15 μM	Sulphite	CV	118
SOx/PBNPs/PPY/ITO	0.50 - 1000.0 μM	0.12 μM	Sulphite	CV	119
CILE	6.0 - 1000.0 μM	4 μM	Sulphite	SWV	120
K-doped Gr/GCE	0.5 to 3900.0 μM	0.2 μM	Sulphite	DPV	121
nano-Au/P3MT/GCE	10.0 - 1000.0 μM	2.3 μM	Nitrite	CA	122
Hb/Gr-AuNP/GCE	0.05 to 1000.0 μM	0.01 μM	Nitrite	CA	123
GNPs/MWCNT/CPE	0.05-250.0 μM	0.01 μM	Nitrite	SWV & CA	124
Au-Pd/rGO/GCE	0.05 to 1000.0 μM	0.02 μM	Nitrite	CA	125
Pd/SWCNT/GCE	2.0 - 1230.0 μM	0.25 μM	Nitrite	DPV	126
Au/ZnO/MWCNTs/GCE	7.8 - 4000.0 μM	4 μM	Nitrite	CA	127
Cu-NDs/RGO/GCE	1.25 - 13.0 mM	0.4 μM	Nitrite	CA	128
PEDOT/MWCNTs-modified SPCEs	0.05 - 1.0 mM	0.96 μM	Nitrite	CA	129
Graphene nanoribbons/GCE	0.5 to 105.0 μM	0.22 μM	Nitrite	CA	130

Conflict of interest

The authors declare no conflict of interest.

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Data Availability Declaration

No new data was generated.

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