

A Review on Recent Advances in Electrochemical Sensing of Phenolic Compounds in Food Matrices: Electrode Materials, Analytical Strategies and Emerging Applications

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Abstract : Phenolic compounds are an important group of naturally occurring and intentionally added constituents of food products. Phenolic acids, flavonoids, stilbenes and related molecules contribute to antioxidant activity, color, flavor and nutritional characteristics, whereas synthetic phenolic antioxidants such as propyl gallate (PG), tert-butylhydroquinone (TBHQ), butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) are used to retard oxidative deterioration. Accurate determination of these compounds is therefore important for food-quality assessment, nutritional evaluation and monitoring of food additives. Conventional chromatographic methods provide high selectivity and accuracy but can involve expensive instrumentation, lengthy analysis and considerable sample preparation. Electrochemical sensing has emerged as an attractive alternative because phenolic molecules are electroactive and can undergo oxidation at electrode interfaces, enabling rapid and sensitive detection. Recent progress in nanostructured carbon materials, metallic and metal-oxide nanomaterials, metal-organic frameworks, molecularly imprinted polymers, screen-printed electrodes and flexible sensing platforms has substantially improved the analytical performance of phenolic sensors. This review discusses the recent development of electrochemical approaches for phenolic-compound detection in food matrices, with particular emphasis on electrode-material design, electrochemical transduction mechanisms, individual phenolic targets, real-food applications and emerging portable systems. Challenges associated with selectivity, electrode fouling, matrix effects, reproducibility and sensor commercialization are also examined. Future research should move beyond achieving increasingly low detection limits and instead emphasize robust real-sample analysis, multiplexed detection, simplified sample preparation, portable instrumentation and data-driven interpretation.

IndexTerms - Phenolic compounds; food matrices; electrochemical sensors; nanomaterials; molecularly imprinted polymers; voltammetry; food analysis; food safety.

1. INTRODUCTION

Phenolic compounds are widely distributed throughout the food chain and represent one of the most chemically diverse classes of bioactive food constituents. They occur naturally in fruits, vegetables, cereals, tea, coffee, wine, herbs and spices and include phenolic acids, flavonoids, tannins, stilbenes and other polyphenolic structures. Their antioxidant properties arise largely from the ability of phenolic functional groups to participate in electron- and hydrogen-transfer reactions. At the same time, excessive or inappropriate levels of some phenolic antioxidants added to foods require analytical control. Consequently, reliable determination of individual phenolic compounds has become important for food quality, authentication and safety. Recent developments in electrochemical sensing have demonstrated that miniaturized electrochemical systems can provide rapid analysis of polyphenols and antioxidant compounds while reducing instrumental requirements compared with conventional chromatographic approaches [1].

Electrochemical detection is particularly attractive because most phenolic compounds contain chemically accessible hydroxyl groups that undergo oxidation at electrode surfaces. This intrinsic electroactivity eliminates the need for an optical label or complex derivatization step in many applications. Improvements in electrode architecture, surface area and electron-transfer kinetics have enabled increasingly sensitive measurements [2]. Nanostructured electrochemical sensors have therefore become an important research area, with carbon nanomaterials, metal nanoparticles and metal oxides being combined to provide greater electroactive area and faster interfacial charge transfer.

The analytical challenge becomes more significant in food matrices because numerous phenolic compounds can coexist at different concentrations and may exhibit similar oxidation potentials. In addition, sugars, organic acids, pigments, vitamins, lipids and other electroactive compounds can affect the electrode response. The distinction between measuring total reducing capacity and quantifying individual phenolic constituents is therefore important. Comparative studies of total polyphenol measurements and chromatographic characterization have shown that bulk antioxidant indices do not necessarily provide the detailed compositional information required for targeted analysis [3].

Electrochemical sensing offers several advantages for this purpose, including low reagent consumption, relatively short analysis time, simple instrumentation and straightforward potential for miniaturization. These properties make electrochemical devices attractive for decentralized food testing and screening [4]. Recent reviews of electrochemical sensors in the food sector have highlighted their growing use for nutrients, additives, contaminants and bioactive compounds, while also emphasizing the importance of validation in genuine food matrices.

2. PHENOLIC COMPOUNDS IN FOOD MATRICES

2.1 Classification and occurrence

Food phenolics can be broadly classified into phenolic acids, flavonoids, stilbenes, lignans and other structurally related compounds. Phenolic acids include hydroxybenzoic acids such as gallic and syringic acids and hydroxycinnamic acids such as caffeic, ferulic and chlorogenic acids. Flavonoids comprise numerous subclasses, including flavonols and flavanols, with compounds such as rutin and quercetin frequently investigated because of their antioxidant properties. The electrochemical behavior of these compounds is closely related to their molecular structures, particularly the number and position of hydroxyl groups and the electronic effects of substituents. Coulometric-array investigations have demonstrated the chemical diversity of food phenolics and the usefulness of electrochemical responses for distinguishing compounds according to their oxidation behavior [5].



Figure 1. Representative food matrices, including coffee and tea, that contain diverse naturally occurring phenolic compounds and other antioxidant constituents.

Phenolic composition varies considerably among food categories. Tea contains abundant catechins and phenolic acids, coffee is particularly rich in chlorogenic acids, fruits contain combinations of hydroxycinnamic acids and flavonoids, and spices and herbs may contain a complex mixture of phenolic acids, flavonoids and volatile phenolic compounds. Processing can alter these profiles through oxidation, hydrolysis, thermal degradation and changes in extractability. Consequently, an electrochemical sensor developed for a pure standard may behave differently when transferred to an actual sample.

Synthetic phenolic antioxidants represent a distinct class of analytically important compounds. PG, TBHQ, BHA and BHT are used primarily to inhibit oxidation in food products, particularly lipid-rich matrices. Their detection is important because the analytical objective is generally quantitative rather than simply qualitative. Recent research on electrochemical systems employing metalloporphyrins and related catalytic interfaces illustrates the continuing development of selective sensing strategies for phenolic antioxidants in food [6].

2.2 Nutritional importance and food-quality considerations

Natural phenolic compounds are frequently associated with antioxidant capacity and other biological effects, but the physiological significance of a food cannot be inferred solely from a total phenolic value. The chemical identity, concentration, bioavailability and interaction among individual constituents must be considered. Consequently, targeted electrochemical determination can complement global antioxidant assays by providing compound-specific information.

In contrast, synthetic antioxidants are intentionally added to protect foods from oxidation. Their presence requires quantitative monitoring and creates a need for selective analytical platforms. Molecularly imprinted electrochemical sensors are particularly attractive in this context because they introduce a recognition mechanism that can distinguish a target molecule from structurally related compounds. Such systems have recently been demonstrated for synthetic phenolic antioxidants, including BHA, where a molecularly imprinted surface combined with nanostructured MoS₂ and silver nanoparticles provided enhanced sensitivity and selectivity [7].

3. ELECTROCHEMICAL PRINCIPLES AND ANALYTICAL STRATEGIES

3.1 Electrooxidation of phenolic compounds

The fundamental electrochemical response of many phenolics arises from oxidation of phenolic hydroxyl groups. Depending on molecular structure and experimental conditions, oxidation may involve proton-coupled electron transfer and formation of quinone-like or related products. The oxidation process is strongly influenced by pH because proton participation affects both thermodynamics and kinetics. Phenolic compounds containing adjacent hydroxyl groups can be particularly electroactive because the resulting oxidation products can be stabilized through resonance.

A recent study using an inexpensive graphite-pencil electrode demonstrated that several phenolic antioxidants exhibit oxidation waves generally associated with a two-electron/two-proton process in the approximately 0.4–0.6 V region versus Ag/AgCl. The same study showed that even an inexpensive carbon substrate can provide useful quantitative information for multiple phenolic antioxidants in food and biological samples [8].

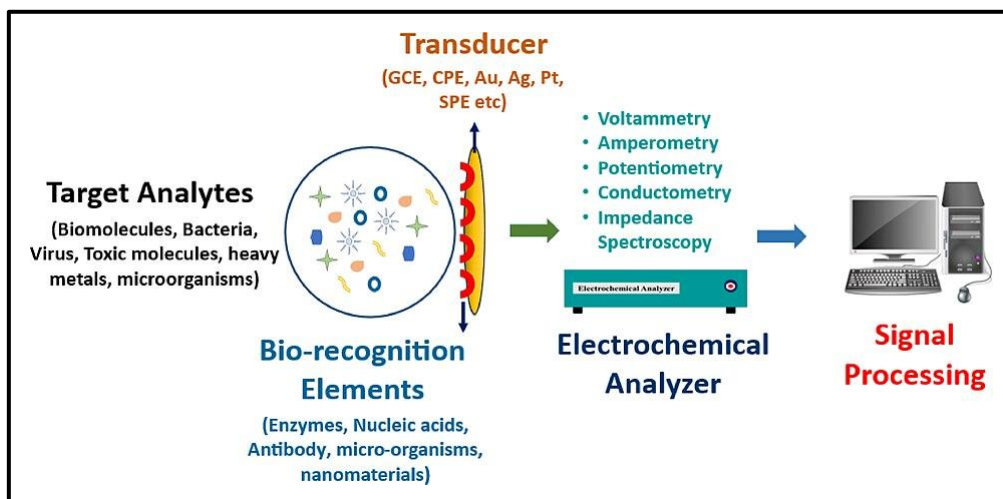


Figure 2. General operating principle of an electrochemical sensing platform showing analyte recognition, electrochemical transduction, signal amplification, processing and data display.

3.2 Voltammetric and amperometric methods

Cyclic voltammetry (CV) is widely used to investigate oxidation and reduction behavior, surface processes and electron-transfer kinetics. It is particularly valuable during sensor development because changes in peak potential and current can reveal the effect of electrode modification. For quantitative measurements, differential pulse voltammetry (DPV) and square-wave voltammetry (SWV) are usually more advantageous because their pulse-based measurement reduces capacitive-current contributions and improves sensitivity.

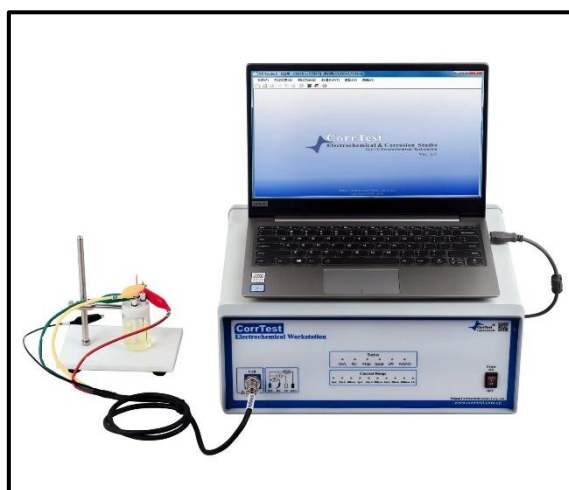


Figure 3. Experimental cyclic-voltammetry measurement using an electrochemical workstation. The electrochemical workstation applies the potential program to the electrode system and records the resulting current response.

Amperometry can also be used when a suitable operating potential is established, especially for continuous monitoring. Electrochemical impedance spectroscopy (EIS) provides complementary information by evaluating interfacial charge-transfer resistance and can be useful during electrode characterization. In complex food analysis, different electrochemical measurements can therefore be combined to investigate both sensor construction and analytical response.

Ratiometric electrochemical sensing has emerged as an additional strategy because it uses the ratio between an analyte-dependent signal and a relatively stable reference signal. This approach can compensate, at least partially, for variations caused by electrode preparation, background current and environmental fluctuations. A recent review of ratiometric electrochemical sensors for food analysis highlights their potential for improving accuracy and reproducibility through built-in signal normalization [9].

3.3 Analytical performance parameters

The performance of a phenolic sensor is commonly evaluated in terms of linear concentration range, sensitivity, limit of detection (LOD), limit of quantification (LOQ), selectivity, repeatability, reproducibility, stability and recovery. An exceptionally low LOD alone does not demonstrate that a sensor is superior for food analysis. The sensor must also provide acceptable recovery in the actual matrix, tolerate interfering species and maintain reliable performance between independently fabricated electrodes.

An additional consideration is sample preparation. A highly sensitive sensor that requires extensive extraction and purification may offer little practical advantage over a chromatographic method. Therefore, recent research has increasingly focused on sensors coupled to simple extraction procedures, inexpensive electrodes and portable electronics.

4. ELECTRODE MATERIALS AND SENSOR-INTERFACE ENGINEERING

4.1 Carbon-based nanomaterials

Carbon-based materials remain among the most important components of electrochemical phenolic sensors because of their electrical conductivity, large surface area and chemical stability. Graphene, reduced graphene oxide, carbon nanotubes, porous carbon, carbon nanofibers and carbon black can provide conductive pathways while also promoting adsorption of aromatic molecules through π - π interactions.

A particularly effective design is the integration of catalytic nanoparticles with porous carbon. A Pd-Ru nanoparticle/N-doped sponge-like carbon electrode demonstrated very high sensitivity toward caffeic acid, with the synergistic action of Pd and Ru increasing the electrochemical response. The sensor was applied successfully to food products, illustrating how a conductive carbon framework and catalytic bimetallic sites can cooperate to improve sensing performance [10].

4.2 Metal and metal-oxide materials

Transition-metal materials provide another important route for increasing the electrocatalytic activity of phenolic sensors. Metal oxides and related transition-metal compounds can offer multiple active sites and favorable adsorption interactions. Their catalytic activity can reduce overpotential, increase oxidation current and potentially improve discrimination between structurally related compounds. A recent review covering transition-metal-based phenolic sensors emphasizes the growing use of transition-metal oxides, chalcogenides and phosphides as alternatives to conventional noble-metal electrocatalysts [11].

Mixed-metal oxide structures can be especially useful because different metal centers may contribute complementary catalytic functions. For example, combining an oxide with graphene or another conductive carbon material can overcome poor intrinsic conductivity while maintaining the catalytic advantages of the oxide phase. Such hybrid interfaces are increasingly common in electrochemical food sensing.

4.3 MOF-derived and porous hybrid materials

Metal-organic frameworks (MOFs) offer a flexible route to highly porous sensing materials and precursors for metal-oxide/carbon composites. Their controlled composition and porosity can provide abundant adsorption and catalytic sites. A Cu-MOF-derived CuO/NiO nanohybrid was developed specifically for catechol detection and exhibited high electrochemical activity, with a reported LOD of 0.0078 μ M. Importantly, the sensor was applied to black and green tea, providing evidence of performance in complex food matrices [12].



Figure 4. Representative high-resolution scanning electron microscopy image of metal-organic framework (MOF) polycrystals illustrating the micro/nanostructured morphology of MOF-based materials. Such porous architectures can provide large accessible surface areas and active sites for electrochemical sensing.

MOFs can also be used indirectly as sacrificial templates. A Ce-MOF-derived Ce-doped PEDOT nanocomposite was developed for rutin determination. The material provided an electrically conductive polymeric framework together with the structural advantages introduced by MOF derivatization and demonstrated application to natural food samples [13].

4.4 Molecularly imprinted polymers

Molecularly imprinted polymers are particularly promising when several phenolics exhibit overlapping oxidation potentials. During synthesis, a template molecule is used to form complementary recognition sites within a polymeric matrix. After template removal, these sites can selectively rebind the target.

A recent MIP/GNP/MWCNT/glassy-carbon sensor for PG achieved a reported detection limit of 6 nM and broad working ranges. The sensor was successfully applied to mayonnaise, black cumin oil and soybean oil [14]. A comparable recognition-based approach was developed for TBHQ in edible oils using an MIP system, showing that selective recognition can be especially valuable in complex lipid matrices where nonspecific electrochemical responses may be problematic [15].

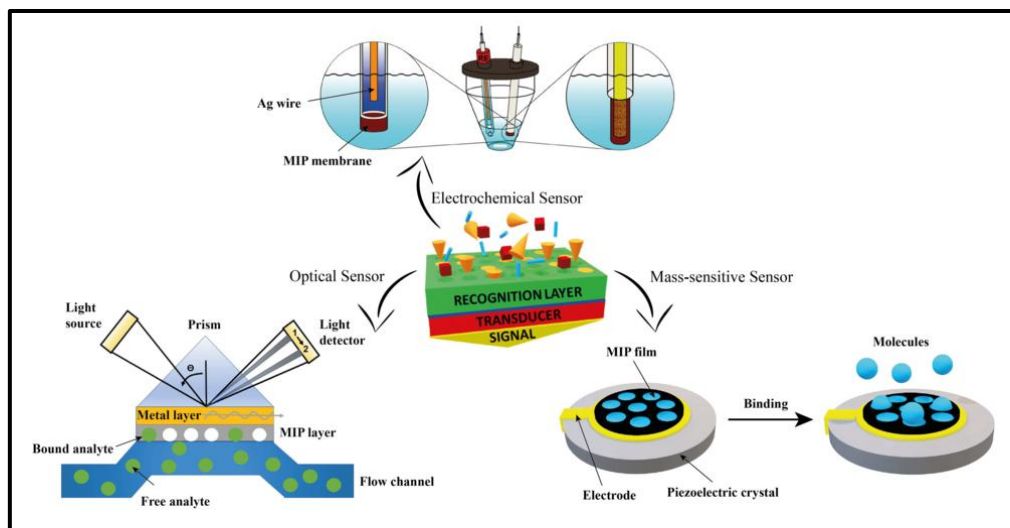


Figure 5. Schematic concept of molecularly imprinted polymers for selective chemical sensing. Molecular recognition cavities generated within the polymer provide selective interaction with the target analyte, which can be coupled with electrochemical signal transduction.

4.5 Screen-printed and flexible electrodes

Screen-printed electrodes provide an attractive platform for disposable and portable food sensors because the working, counter and reference electrodes can be integrated on a compact substrate. Their reproducible mass fabrication and small sample requirement facilitate point-of-use analysis. An Au-nanoparticle/kaolinite-modified screen-printed sensor provided nanomolar-level gallic-acid detection and was validated using black tea and pomegranate juice [16].

Flexible electrodes offer a further step toward in situ analysis. A laser-induced graphene sensor enhanced with MXene and MoS₂ nanosheets was developed for gallic-acid measurement directly in plant leaves. The sensor covered 1–1000 μ M and demonstrated field-compatible flexible operation, illustrating how electrochemical systems may eventually extend from extracted food samples toward direct plant and food monitoring [17].

5. ELECTROCHEMICAL DETECTION OF REPRESENTATIVE PHENOLIC COMPOUNDS

5.1 Catechol

Catechol is one of the most frequently used model phenolics in electrochemical sensor research because its adjacent hydroxyl groups produce a strong and readily measurable oxidation response. Its simplicity also makes it useful for evaluating electrocatalytic interfaces and examining the influence of electron-transfer kinetics. However, oxidation products can participate in follow-up reactions or adsorb to electrode surfaces, creating the possibility of surface fouling.

The Cu-MOF/CuO/NiO system discussed above demonstrates the potential of hierarchical porous nanohybrids for catechol detection in tea. The successful analysis of black and green tea is particularly relevant because naturally occurring tea phenolics can produce substantial interference [12]. More broadly, future catechol sensors should focus on discriminating catechol from hydroquinone, resorcinol and other coexisting phenolic compounds rather than maximizing sensitivity alone.

5.2 Caffeic acid

Caffeic acid is a hydroxycinnamic acid commonly found in coffee, fruits, vegetables and many plant-derived foods. Its catechol moiety makes it strongly electroactive and attractive for evaluation of catalytic sensor surfaces. Bimetallic Pd–Ru nanoparticles dispersed in N-doped porous carbon produced an especially sensitive caffeic-acid response, demonstrating the benefit of combining high surface area with catalytic metal sites [10].

Another approach employed a GNR/CoFe₂O₄@NiO composite together with an ionic-liquid component to construct a caffeic-acid sensor. The hybrid interface improved electrocatalytic response and enabled analysis in beverages and other real samples [18]. Such systems highlight a common trend in current research: individual materials are increasingly being combined to provide conductivity, catalytic activity and analyte enrichment simultaneously.

5.3 Gallic acid

Gallic acid is an important trihydroxybenzoic acid found in tea, fruits and various plant-derived products. Its multiple hydroxyl groups make it highly electroactive, but they can also contribute to surface interactions and fouling. A Co/Fe-based carbon nanopolyhedral composite deposited onto a glassy carbon electrode achieved a reported LOD of 1.30 nM and was applied to apples, grapes, tomatoes and red wine [19].

Another recent strategy integrated nanochannel film with nanocarbon materials to improve gallic-acid sensing. The resulting electrode exploited the combination of controlled diffusion and conductive nanocarbon interfaces and demonstrated two linear concentration ranges, illustrating how layered structures can influence both sensitivity and selectivity [20]. Such architectures may be particularly useful where electroactive interferents are present because selective transport through the interface can complement the intrinsic electrochemical response.

5.4 Chlorogenic acid

Chlorogenic acid is one of the most important phenolic constituents of coffee and several medicinal or food plants. Its quantitative determination is relevant to quality control because processing and storage can alter its concentration. An electrochemical platform using a carbon-based composite was successfully applied to chlorogenic-acid determination in Mirra coffee, demonstrating the feasibility of targeted analysis in a complex beverage matrix.

The development of portable instrumentation is particularly relevant for chlorogenic acid. A hierarchically porous biomass-derived carbon sensor demonstrated a 6.2 nM LOD and was integrated with a smartphone-based workstation. The system was used for on-site analysis of chlorogenic acid in herbal materials and fresh plant leaves, illustrating how electrochemical sensing can be connected to readily available digital devices [21].

5.5 Propyl gallate

Propyl gallate is a synthetic ester of gallic acid and is used as a food antioxidant. Its aromatic structure provides electrochemical activity, while its hydrophobic character can complicate analysis in lipid-containing matrices. The MIP/GNP/MWCNT sensor developed specifically for PG illustrates how electrochemical transduction can be combined with molecular recognition. The reported 6 nM detection limit and successful analysis of mayonnaise and edible oils show the potential of this strategy for selective food-additive monitoring [14].

5.6 TBHQ, BHA and BHT

TBHQ is an important synthetic phenolic antioxidant used to delay oxidation in fat-containing foods. Its detection has received considerable attention because direct single-signal electrochemical measurements may be affected by matrix composition. A recent ratiometric sensor based on SWCNH/T-PEDOT nanocomposites used dual-signal analysis to improve quantification in foodstuffs [22]. A separate Co-nanocluster/CNT/methylene-blue ratiometric platform similarly demonstrated TBHQ determination in real edible oils, indicating that internally referenced electrochemical signals are becoming an important strategy for antioxidant analysis [23].

BHA presents comparable challenges because structurally related compounds can contribute to overlapping electrochemical signals. The molecularly imprinted MoS₂/Ag nanoparticle system discussed earlier demonstrates how recognition cavities can improve selective determination [7].

BHT is relatively hydrophobic and can occur in food as well as food-packaging-related applications. A recent sensor using a rare-earth/metal-oxide/graphene nanocomposite was evaluated using CV, EIS and DPV and successfully targeted BHT in food and other samples [24]. These studies show that synthetic antioxidants are an important testing ground for evaluating whether electrochemical sensing can achieve both sensitivity and matrix tolerance.

5.7 Other phenolic compounds

Electrochemical sensing is expanding toward phenolic compounds that are important for flavor, authentication and nutritional characterization. Vanillin is a prominent example. A sodium-montmorillonite/Au@ZIF-67 composite electrode was developed for vanillin determination in food samples. The nanoclay provided adsorption capability, the ZIF-derived component contributed active sites and gold nanoparticles enhanced electrical conductivity. The authors reported a two-electron/two-proton electrooxidation process for vanillin, illustrating how electrochemical and materials studies can be combined to elucidate sensing mechanisms [25].

Syringic acid is another phenolic acid that has been investigated using molecular imprinting. An acrylonitrile-MIP-coated graphite electrode produced a 10–100 µM linear range and an LOD of 0.32 µM, with good repeatability, reproducibility and selectivity in food extracts [26]. Ferulic acid and other hydroxycinnamic acids similarly represent promising targets because their occurrence is associated with cereals, fruits, beverages and plant-derived products. Broadening the analyte scope is important if electrochemical sensing is ultimately to provide comprehensive phenolic profiling rather than determination of isolated compounds.

6. ANALYSIS OF REAL FOOD MATRICES

The transition from standard solutions to real food matrices represents one of the most important challenges in electrochemical phenolic sensing. Actual samples may contain proteins, lipids, carbohydrates, minerals, pigments, organic acids and several electroactive molecules. These constituents can alter diffusion, adsorption and charge transfer at the electrode surface. Therefore, recovery studies using genuine food samples are essential when evaluating practical sensor performance.

Edible oils are particularly demanding because of their low polarity and limited compatibility with aqueous electrochemical media. Successful TBHQ sensing in edible oils using porous carbon, MOF-based and molecularly imprinted interfaces demonstrates that appropriate sample extraction combined with selective electrode chemistry can address this challenge. Tea and coffee are also complex because they contain many phenolic constituents simultaneously. The catechol and chlorogenic-acid sensors discussed above demonstrate the potential of targeted electrochemical methods when the analyte and matrix are carefully matched.

Portable electrochemical systems are especially promising for agricultural products and food ingredients because they can reduce the dependence on centralized laboratories. Smartphone-operated chlorogenic-acid detection is an important example of this trend [21]. Screen-printed sensors offer another practical route by integrating the three-electrode configuration into an inexpensive disposable platform [16].

Nevertheless, many reported sensors still require laboratory preparation of the food sample, supporting electrolyte adjustment and controlled electrode conditioning. The next step is therefore to develop workflows in which extraction, filtration, dilution and electrochemical measurement are simplified into a small number of operations.

7. CHALLENGES AND LIMITATIONS

7.1 Matrix interference and selectivity

The major analytical challenge is the simultaneous presence of electroactive compounds. Phenolic acids and flavonoids can have closely spaced oxidation potentials, while ascorbic acid and other antioxidants can interfere with measurement. Molecular recognition, charge-selective membranes, molecular imprinting and electrode arrays can provide greater selectivity than simple catalytic amplification alone.

Biological recognition is another possibility. Oxidoreductases such as laccase, tyrosinase and peroxidase can recognize broad families of phenolic substrates and have therefore been incorporated into electrochemical biosensors. Recent work on oxidoreductase-based biosensors highlights the role of enzymatic recognition, immobilization strategies and nanomaterials in the selective determination of phenolic antioxidants in food and beverages [27].

7.2 Electrode fouling and reproducibility

Electrode fouling remains a major concern, especially for phenolic molecules whose oxidation products can polymerize or adsorb strongly onto surfaces. Fouling can cause decreasing peak currents, shifts in oxidation potentials and loss of sensitivity. Disposable electrodes can reduce the need for regeneration, whereas antifouling coatings and optimized potential windows may extend electrode lifetime.

Nanomaterial-based films can also introduce reproducibility problems because variations in loading, morphology, particle size and film thickness may alter the active surface. To facilitate commercialization, fabrication protocols must be standardized and performance should be evaluated across independently prepared electrode batches rather than using repeated measurements on a single sensor.

8. EMERGING DIRECTIONS AND FUTURE PERSPECTIVES

A major direction in electrochemical food analysis is the development of ratiometric, portable and data-assisted sensing. Ratiometric systems can reduce errors caused by fluctuations in background signal and electrode properties [9]. Smartphone-operated systems can provide immediate data visualization and potentially transmit results to centralized databases. Flexible sensors offer the possibility of direct analysis of plant tissues or food surfaces, while screen-printed platforms are suitable for disposable testing.

Chemometric analysis is also beginning to change the interpretation of electrochemical data. Instead of relying on a single oxidation peak, entire voltammetric datasets can be analyzed using multivariate algorithms. A 2025 study employed second-order voltammetric data and multivariate curve resolution–alternating least squares (MCR-ALS) for gallic-acid determination in the presence of unmodeled interferences, demonstrating how mathematical information extraction can improve analytical resolution in complex food samples [28].



Figure 6. Representative potentiostat used for electrochemical measurements. Miniaturization of potentiostats is an important step toward portable and point-of-use electrochemical analysis of food constituents.

For future sensor development, the objective should therefore shift from simply obtaining extremely low LODs toward achieving reliable performance under realistic conditions. A practical food sensor should require minimal sample preparation, tolerate matrix variability, be inexpensive to fabricate, exhibit good batch-to-batch reproducibility and provide results that can be readily interpreted by non-specialist users. Integration of nanostructured electrocatalysts, selective recognition layers, disposable electrodes, portable potentiostats and computational analysis could enable such systems.

9. CONCLUSION

Electrochemical sensing has become an important analytical strategy for the detection of phenolic compounds in food matrices. Recent progress in carbon nanomaterials, metal and metal-oxide catalysts, MOF-derived structures, molecularly imprinted polymers, screen-printed electrodes, flexible platforms and ratiometric signal processing has greatly expanded the capabilities of phenolic sensors. Successful determination of catechol, caffeic acid, gallic acid, chlorogenic acid, PG, TBHQ, BHA, BHT, vanillin, syringic acid and related compounds demonstrates the breadth of the field. However, practical implementation still requires better control of matrix effects, electrode fouling, fabrication reproducibility and selective discrimination among structurally related analytes. The integration of advanced electrode materials with molecular recognition, portable instrumentation and chemometric analysis represents a promising route toward rapid, reliable and field-deployable food analysis.

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