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Natural Origins, Electrochemical Precision: Plant-Based Materials in Modern Sensing Devices

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أصول طبيعية ودقة كهروكيميائية: مواد نباتية المنشأ في أجهزة الاستشعار الحديثة

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Abstract:

Electrochemical sensors represent a cornerstone of modern analytical technology due to their high sensitivity, selectivity, and rapid response. In recent years, the integration of plant-derived materials into sensor platforms has emerged as a promising avenue to enhance sustainability, reduce reliance on synthetic components, and introduce unique biofunctionalities. Medicinal plants, rich in phytochemicals such as polyphenols, flavonoids, alkaloids, and terpenes, offer a renewable source of redox-active and surface-modifying agents. These compounds not only improve electron transfer kinetics but also confer biocompatibility and selectivity toward specific analytes. This review explores recent advances in the use of medicinal plant extracts, carbonized plant biomass, and plant-based composites for electrochemical sensing applications. Case studies highlight their role in detecting environmental pollutants, foodborne contaminants, and clinical biomarkers. Emphasis is placed on material synthesis, sensor architecture, and performance metrics, offering insight into both fundamental mechanisms and practical applications. The review also addresses current limitations and outlines future directions for scalable fabrication and regulatory integration of plant-based electrochemical sensors.

Keywords: Plant-based materials; Electrochemical sensors; Green synthesis; Phytochemicals; Nanomaterials; Biosensing; Natural antioxidants

الملخص

تُعدّ المستشعرات الكهروكيميائية حجر الزاوية في تكنولوجيا التحليل الحديثة نظرًا لحساسيتها العالية وانتقائيتها وسرعة استجابتها. في السنوات الأخيرة، برز دمج المواد المشتقة من النباتات في منصات الاستشعار كسبيل واعد لتعزيز الاستدامة، وتقليل الاعتماد على المكونات الاصطناعية، وإضفاء وظائف حيوية فريدة. تُوفّر النباتات الطبية، الغنية بالمواد الكيميائية النباتية مثل البوليفينولات والفلافونويدات والقلويدات والتربينات، مصدرًا متجددًا لعوامل الأكسدة والاختزال وعوامل تعديل الأسطح. لا تُحسّن هذه المركبات حركية نقل الإلكترون فحسب، بل تُضفي أيضًا التوافق الحيوي والانتقائية تجاه مواد تحليلية مُحددة. تستعرض هذه المراجعة أحدث التطورات في استخدام مستخلصات النباتات الطبية، والكتلة

الحيوية النباتية المُفحمة، والمركبات النباتية لتطبيقات الاستشعار الكهروكيميائي. تُسلّط دراسات الحالة الضوء على دورها في الكشف عن الملوثات البيئية، والملوثات المنقولة بالغذاء، والمؤشرات الحيوية السريرية. وينصبّ التركيز على تصنيع المواد، وبنية المستشعر، ومقاييس الأداء، مما يُقدّم نظرة ثاقبة على كلٍ من الآليات الأساسية والتطبيقات العملية. كما تتناول المراجعة القيود الحالية وتحدد التوجهات المستقبلية للتصنيع القابل للتطوير والتكامل التنظيمي لأجهزة الاستشعار الكهروكيميائية النباتية.

الكلمات المفتاحية: مواد نباتية، مستشعرات كهروكيميائية، تخليق أخضر، مركبات كيميائية نباتية، مواد نانوية، استشعار حيوي، مضادات أكسدة طبيعية.

Introduction

The growing need for accurate, rapid, and cost-effective detection of chemical and biological species has spurred significant interest in the development of electrochemical sensors. These devices are widely applied in clinical diagnostics, environmental monitoring, food safety, and industrial process control [1]. Traditional sensor materials, however, often rely on rare metals, synthetic polymers, and high-energy fabrication processes, raising concerns regarding their environmental footprint and biocompatibility [2]. In response to these challenges, researchers have increasingly turned to natural materials as sustainable alternatives. Among these, medicinal plants have gained particular attention for their rich phytochemical profiles and ecological availability. These plants contain secondary metabolites such as tannins, quinones, flavonoids, phenolic acids, and terpenoids, many of which possess redox activity and can interact selectively with target analytes [3–5]. Plant-based materials can serve in multiple roles within electrochemical sensors: as active electrode modifiers, electrocatalysts, immobilization matrices, or even precursors for carbon nanomaterials through pyrolysis. For instance, the carbonization of *Moringa oleifera* leaves yields porous carbon with excellent conductivity and electrocatalytic behavior toward heavy metal ions [6]. Likewise, polyphenol-rich extracts from *Camellia sinensis* have been employed as green reducing agents and stabilizers in the synthesis of metal nanoparticle-decorated electrodes for glucose sensing [7]. Moreover, the use of plant-derived materials aligns with the principles of green chemistry, supporting the transition to low-cost, eco-friendly sensing technologies. Such approaches reduce chemical waste, utilize renewable feedstocks, and often enable room-temperature fabrication processes [8].

This review provides a comprehensive overview of the current landscape in plant-based electrochemical sensors, with a focus on materials sourced from medicinal plants. It critically examines the methods of preparation, sensor performance parameters (e.g., sensitivity, limit of detection, stability), and application fields. Special attention is paid to hybrid systems combining plant-based materials with nanostructured metals or conducting polymers to overcome performance trade-offs. Finally, we address challenges in reproducibility, standardization, and scale-up, proposing pathways toward the broader adoption of plant-derived sensing platforms.

2. Phytochemicals as Functional Electrochemical Components

Plant-derived molecules offer a vast reservoir of electroactive compounds that serve not only as structural modifiers for electrode surfaces but also as active redox participants. Among these, phenolics, flavonoids, alkaloids, terpenoids, and tannins are especially notable due to their diverse redox behaviors and capacity for analyte interaction. These characteristics render them valuable for the development of sustainable and high-performance electrochemical sensors[9,10]. Phenolic compounds, such as gallic acid, catechin, and caffeic acid, possess hydroxyl groups that undergo reversible oxidation, forming the basis of numerous antioxidant detection systems. When incorporated into sensor platforms—either by direct immobilization or via hybrid composites—they significantly improve electron transfer kinetics and sensitivity toward oxidizable species [11,12]. Flavonoids, particularly quercetin and rutin, exhibit distinct oxidation peaks under voltammetric conditions. These molecules have been successfully used in designing graphene- and carbon paste-based sensors capable of detecting trace levels of reactive oxygen species and metal ions [13]. Alkaloids, including berberine and morphine derivatives, provide redox-active frameworks suitable for the detection of pharmaceuticals and bioanalytes. Their inclusion in sensing materials enhances analyte specificity through electrostatic and π-π interactions, making them effective for applications in bioanalysis and clinical diagnostics [14,15]. Terpenoids, often derived from essential oils, contribute both structural and functional benefits to sensor membranes. Volatile compounds such as limonene and linalool have been immobilized on modified electrodes for the selective detection of volatile organic compounds (VOCs), thanks to their lipophilicity and chemical reactivity [16]. Tannins, a class of polyphenolic compounds, exhibit high binding affinities toward heavy metals and organic toxins. Tannin-functionalized electrodes demonstrate notable sensitivity and stability in detecting trace metal contaminants such as lead and cadmium in aqueous environments [17–19]. An overview of the main phytochemical classes, their plant sources, electrochemical roles, and associated analytes is presented in **Table 1**. This compilation underscores the versatility of natural compounds in constructing functional and eco-friendly sensing platforms.

Table 1. Selected Phytochemicals from Medicinal Plants Used in Electrochemical Sensor Design

Compound Class	Example Phytochemicals	Source Plant(s)	Electrochemical Role	Target Analyte(s)	Reference
Phenolics	Gallic acid, Caffeic acid	*Punica granatum*, *Camellia sinensis*	Redox-active species, radical scavengers	Antioxidants, ROS	[11], [12]
Flavonoids	Quercetin, Rutin	*Ginkgo biloba*, *Citrus sinensis*	Oxidation-based detection	Free radicals, heavy metals	[13]
Alkaloids	Berberine, Morphine	*Berberis vulgaris*, *Papaver somniferum*	Electroactive complexation	Dopamine, codeine, opiates	[14], [15]
Terpenoids	Limonene, Linalool	*Citrus limon*, *Lavandula spp.*	VOC sensors, membrane enhancement	Organic solvents, VOCs	[16]
Tannins	Tannic acid, Ellagitannin	*Quercus spp.*, *Camellia sinensis*	Metal binding, redox activity	Pb^{2+}, Cd^{2+}, Fe^{3+}	[17], [18], [19]

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3. Plant-Based Nanomaterials for Electrochemical Sensor Platforms

Advances in green chemistry have enabled the synthesis of functional nanomaterials using plant extracts as reducing, capping, and stabilizing agents. These plant-based nanomaterials exhibit high surface-to-volume ratios, tunable surface chemistry, and enhanced electron mobility—critical attributes for high-performance electrochemical sensors. Unlike traditional chemical methods, phytosynthesis avoids toxic reagents and complex reaction conditions, making it both eco-friendly and scalable.

3.1. Green-Synthesized Metal Nanoparticles

Metal nanoparticles (NPs) such as silver (Ag), gold (Au), and copper (Cu) are widely synthesized using plant extracts rich in polyphenols and flavonoids. These compounds reduce metal ions to zero-valent nanoparticles and simultaneously act as stabilizers. For example, *Azadirachta indica* leaf extract has been used to synthesize AgNPs with uniform morphology, which were subsequently employed to fabricate a sensor for nitrite detection with excellent selectivity and sensitivity [20]. Gold nanoparticles synthesized using *Camellia sinensis* extracts exhibit high electrochemical conductivity and biocompatibility, making them ideal for biosensor platforms detecting glucose or cancer biomarkers [21]. Similarly, copper oxide nanoparticles from *Moringa oleifera* leaves have demonstrated excellent catalytic performance in hydrogen peroxide detection [22].

3.2. Carbon-Based Nanostructures from Biomass

Plant biomass can be converted into carbonaceous nanomaterials such as biochar, carbon nanotubes (CNTs), and graphene-like nanosheets via pyrolysis or hydrothermal carbonization. These carbon materials are often doped with heteroatoms (e.g., N, S, or O) when derived from nitrogen-rich precursors, thereby enhancing their electrochemical properties [23]. For instance, nitrogen-doped carbon derived from *Citrus aurantium* peels exhibited high electrocatalytic activity when integrated into a sensor for dopamine detection. This green carbon was reported to outperform conventional CNTs in terms of conductivity, surface area, and biocompatibility [24]. Moreover, plant-derived graphene nanosheets functionalized with phenolic residues have shown promise in sensors for pesticides and heavy metal ions [25].

3.3. Hybrid Nanocomposites with Natural Polymers

Plant-sourced nanomaterials are frequently integrated with natural polymers such as cellulose, lignin, or chitosan to enhance their mechanical flexibility and chemical stability. These hybrid platforms exhibit synergistic properties—combining the high conductivity of nanomaterials with the structural versatility of biopolymers [26]. A notable example involves lignin-stabilized AgNPs embedded in a cellulose matrix, yielding a flexible, paper-based electrochemical sensor capable of detecting ascorbic acid and uric acid simultaneously [27]. Additionally, composite films incorporating turmeric-derived carbon dots and chitosan have been used for real-time monitoring of food spoilage indicators [28].

3.4. Advantages and Performance Summary

The integration of plant-based nanomaterials into electrochemical sensors not only addresses the need for greener fabrication methods but also delivers devices with enhanced **sensitivity,** selectivity, reproducibility, and stability. These materials often outperform their chemically synthesized counterparts, especially in detecting analytes in complex matrices such as serum, wastewater, or food extracts. Table 2 summarizes selected examples of plant-based nanomaterials used in electrochemical sensing, along with their target analytes and analytical performance.

Table 2. Selected Plant-Based Nanomaterials and Their Application in Electrochemical Sensors

Nanomaterial Type	Plant Source	Target Analyte	Detection Limit	Sensor Type	Reference
AgNPs	*Azadirachta indica*	NO_2^-	0.1 µM	Amperometric	[20]
AuNPs	*Camellia sinensis*	Glucose	1.2 µM	Enzymatic biosensor	[21]
CuO NPs	*Moringa oleifera*	H_2O_2	0.3 µM	Voltammetric	[22]
N-doped Carbon	*Citrus aurantium* peel	Dopamine	0.05 µM	Differential pulse voltammetry	[24]
Plant Graphene	*Spinacia oleracea*	Pb^{2+}	0.2 µg/L	Anodic stripping voltammetry	[25]
Lignin–AgNPs–Cellulose	*Populus tremula* bark	Ascorbic acid, Uric acid	0.3 µM, 0.5 µM	Paper sensor	[27]

4. Mechanisms of Signal Transduction and Selectivity in Plant-Based Electrochemical Sensors

The effectiveness of any electrochemical sensor depends not only on the material's conductivity but also on its transduction mechanism and molecular recognition capabilities. In sensors using plant-based nanomaterials, signal generation is often mediated by a combination of redox-active sites, surface functional groups, and interactions with the analyte through adsorption, coordination, or covalent bonding.

4.1. Electron Transfer and Surface Redox Activity

Electrochemical signal transduction is typically governed by Faradaic processes, where the analyte undergoes oxidation or reduction at the electrode surface. Plant-derived nanomaterials often carry electron-donating or withdrawing groups—such as hydroxyl, carboxyl, or quinonoid moieties—that facilitate or modulate this electron transfer [29]. In carbon materials obtained from citrus peel pyrolysis, abundant quinone-like structures were shown to participate in the redox process during dopamine detection, enhancing sensitivity and peak current resolution [30]. Similarly, flavonoid-capped gold nanoparticles enable direct electron transfer between redox enzymes and electrodes without the need for mediators, a major advantage for biosensor applications [31].

4.2. Role of Phytochemical Functionalization

The phytochemical coating of green-synthesized nanoparticles not only stabilizes the material but also contributes to selective recognition. For instance, tannin-functionalized silver nanoparticles from *Terminalia chebula* selectively interacted with phosphate ions through hydrogen bonding and π–π interactions, yielding a distinct current response [32]. Moreover, polyphenolic groups in plant-derived carbon dots can interact with amino acids, pesticides, or nitroaromatics via hydrogen bonding or π–π stacking, thus providing analyte-specific current modulation [33].

4.3. Molecular Recognition via Biopolymer Interfaces

Natural polymers such as cellulose, chitosan, or lignin, when combined with plant-based nanomaterials, can introduce specific binding sites or functional groups that interact selectively with the target analyte. These biopolymers also enhance the electrochemical window and maintain the material's structural integrity during repeated cycles [34]. For instance, a hybrid nanocomposite of *Musa paradisiaca* starch and graphene oxide exhibited selective detection of uric acid, owing to the interaction between the hydroxyl groups of starch and the analyte, confirmed by changes in oxidation peak current [35].

4.4. Signal Amplification and Catalytic Activity

In many biosensing platforms, plant-derived nanomaterials serve as electrocatalysts, amplifying the signal through enhanced electron transfer kinetics or catalytic turnover. Copper oxide nanoparticles synthesized from *Ocimum sanctum* exhibited peroxidase-like activity, which enabled sensitive detection of hydrogen peroxide and glucose through catalytic oxidation [36]. Signal amplification is further achieved through nanostructuring, which increases the electroactive surface area. Porous carbon frameworks derived from *Syzygium aromaticum* clove buds demonstrated high double-layer capacitance and acted as robust supports for enzyme immobilization, resulting in amplified amperometric response to xanthine [37].

4.5. Enhancing Selectivity in Complex Matrices

Selectivity remains a key challenge in sensor design, particularly when dealing with real-world samples containing multiple interferents. The combination of intrinsic functional groups, surface charge modulation, and affinity-based recognition in plant-based materials addresses this challenge effectively. In recent work, carbonaceous nanomaterials synthesized from *Punica granatum* peel were integrated into a voltammetric sensor capable of distinguishing ascorbic acid, dopamine, and uric acid simultaneously, each producing separate, well-defined oxidation peaks [38].

5. Applications in Environmental, Biomedical, and Food Sensing

Plant-based electrochemical sensors have rapidly transitioned from conceptual frameworks to real-world tools across multiple domains. Their biocompatibility, eco-friendliness, and cost-effectiveness make them especially attractive for on-site and portable diagnostics. This section highlights key application areas where such sensors have demonstrated high performance and practicality.

5.1. Environmental Monitoring

The detection of pollutants in air, water, and soil is a critical global challenge. Electrochemical sensors incorporating plant-derived nanomaterials offer high selectivity and low detection limits for heavy metals, pesticides, and emerging contaminants. For example, an electrochemical platform based on carbonized *Moringa oleifera* leaves enabled the sensitive detection of Pb(II) and Cd(II) ions in wastewater, with detection limits reaching as low as 0.3 µg/L [39]. The presence of residual carboxyl and hydroxyl groups facilitated chelation with the metal ions, contributing to high selectivity. Another sensor utilizing lignin-stabilized gold nanoparticles showed excellent sensitivity toward the herbicide paraquat in agricultural runoff, with a linear range of 0.1–100 µM and excellent stability over repeated use [40].

5.2. Biomedical Diagnostics

Plant-based nanomaterials exhibit intrinsic biocompatibility, making them ideal candidates for biomedical sensing. Several studies have reported their use in the detection of clinically relevant biomarkers such as glucose, uric acid, dopamine, and cancer-related proteins. A recent design employed carbon dots derived from *Camellia sinensis* tea leaves to fabricate a non-enzymatic glucose sensor with a detection limit of 0.8 µM and excellent performance in serum samples [41]. Their oxygen-rich surface functionalities contributed to strong electrocatalytic behavior. Similarly, a sensor based on *Aloe vera*-mediated zinc oxide nanorods successfully detected uric acid in human urine with high selectivity against interfering compounds like ascorbic acid and glucose [42]. The phytochemicals acted both as reducing agents and dopants, enhancing conductivity and electron transfer kinetics. In biosensor development, plant-derived nanomaterials also serve as immobilization matrices for enzymes or antibodies. A chitosan–plant extract composite was recently used to detect carcinoembryonic antigen (CEA) via electrochemical impedance spectroscopy with a detection limit of 0.02 ng/mL [43].

5.3. Food Quality and Safety

The monitoring of food freshness, spoilage, and contamination is another area where plant-based electrochemical sensors have made significant inroads. These sensors are especially useful for detecting foodborne toxins, preservatives, and spoilage indicators. Carbonized orange peel combined with polyaniline was developed into a voltammetric sensor capable of detecting nitrite in processed meats down to 0.1 µM [44]. The synergy between conductive polymer and porous biochar enhanced analyte adsorption and electron transfer. In another study, polyphenol-capped silver nanoparticles synthesized using *Mentha piperita* extract were used to detect histamine in canned fish—a key spoilage indicator—via chronoamperometry. The sensor showed a response time of under 5 seconds and excellent selectivity in real food matrices [45]. Beyond contaminants, such sensors have also been explored for detecting sugars, acids, and other nutritional parameters. A voltammetric sensor based on *Beta vulgaris* (beetroot)-derived carbon was shown to accurately monitor citric acid levels in fruit juices with a detection limit of 1.2 µM [46].

6. Challenges and Future Perspectives

Despite their promise, the widespread adoption and commercialization of plant-based electrochemical sensors face several scientific and technological hurdles. These challenges primarily stem from variability in natural raw materials, limitations in long-term stability, and scalability constraints.

6.1. Material Variability and Standardization

One of the principal challenges in using plant-derived materials lies in batch-to-batch variability. The chemical composition of plant extracts, even from the same species, can vary significantly depending on factors such as geography, harvest time, and extraction conditions [47]. Such inconsistency may lead to fluctuations in sensor sensitivity, response time, and selectivity. To address this, future research should focus on standardized extraction protocols, quality control during synthesis, and in situ chemical fingerprinting of the derived nanomaterials. Incorporating machine learning to correlate extraction variables with sensor performance could enhance reproducibility [48].

6.2. Sensor Stability and Shelf Life

Electrochemical sensors made from biogenic materials often suffer from limited shelf life due to biodegradation, environmental sensitivity (e.g., moisture, light), and structural instability. For example, sensors using plant-synthesized metal nanoparticles may undergo oxidation or aggregation over time, reducing their sensitivity [49]. To enhance longevity, efforts are being directed toward composite systems—e.g., integrating plant-based materials with conductive polymers, silica coatings, or carbon nanotubes to improve mechanical robustness and oxidative resistance [50]. Further, encapsulation techniques such as electrospun fiber matrices or freeze-dried composites may offer protective environments while preserving reactivity.

6.3. Selectivity in Complex Matrices

In real-world applications, sensors must function within complex matrices—such as blood, wastewater, or food slurries—where numerous interfering species may exist. Achieving high selectivity remains a significant bottleneck. While plant-based sensors exhibit strong affinity toward certain analytes due to residual phytochemicals, distinguishing closely related species (e.g., dopamine vs. ascorbic acid) remains difficult [51]. Advanced strategies such as molecular imprinting, aptamer conjugation, or hybridization with enzyme-mimicking nanozymes may help to improve target recognition. Integrating microfluidics for pre-filtration or separation could also enhance signal-to-noise ratios in complex matrices [52].

6.4. Scale-Up and Industrial Translation

Most plant-based electrochemical sensors are still confined to laboratory-scale studies. The translation to mass production and market readiness is hindered by challenges in ensuring consistent raw material supply, scalable synthesis, and device integration. Developing green, low-cost fabrication methods—such as screen printing, inkjet printing, or 3D bioprinting—tailored for plant-derived inks and substrates may offer scalable pathways. Furthermore, incorporating these sensors into wearable platforms or IoT-based environmental monitors could catalyze their transition to commercial products [53].

6.5. Regulatory and Safety Considerations

Although plant-derived materials are generally regarded as safe, their regulatory approval—especially for clinical or food-contact applications—requires thorough assessment. This includes toxicity studies of the final sensor components, leaching potential, and biocompatibility [54]. Collaborative efforts between material scientists, toxicologists, and regulatory bodies are needed to streamline safety evaluations and establish regulatory frameworks specific to bio-derived sensor technologies.

Conclusions

The integration of plant-based materials into electrochemical sensing platforms represents a significant paradigm shift toward green, accessible, and multifunctional analytical devices. Leveraging the rich chemical complexity of natural extracts, particularly polyphenols, flavonoids, and other redox-active phytochemicals, researchers have engineered diverse nanostructures such as metal nanoparticles and doped carbon frameworks that exhibit excellent electrochemical properties.

This chapter has demonstrated how plant-derived components can serve as reductants, capping agents, or even primary sensing interfaces, enabling the fabrication of sensors capable of detecting biologically and environmentally relevant analytes with high sensitivity and reasonable selectivity. The dual advantage of ecological sustainability and functional versatility positions these materials as attractive candidates in the development of low-cost, field-deployable diagnostic and monitoring technologies.

Nevertheless, several challenges must be addressed, particularly in ensuring material reproducibility, enhancing sensor durability, and achieving adequate selectivity in complex real-world matrices. Furthermore, scalability and compliance with regulatory standards remain critical bottlenecks for industrial implementation and commercialization.

Future research should prioritize multidisciplinary strategies that integrate materials science, green chemistry, data-driven modeling, and engineering design to resolve these limitations. The convergence of natural product chemistry with modern electrochemical engineering, especially in applications such as wearable devices, point-of-care diagnostics, and smart environmental monitoring, represents a promising direction for sustainable sensor innovation. In summary, plant-based electrochemical sensors occupy a unique space at the intersection of traditional botanical knowledge and cutting-edge technology, offering a viable path toward affordable, biocompatible, and environmentally responsible analytical solutions aligned with global sustainability objectives.

Author Contributions

N. N. Salah: Conceptualization, supervision, project administration, critical revision of the manuscript, and final approval. **Rema Amara Abdalla Ballg:** Literature search, data curation, investigation, writing—original draft preparation, and visualization. **Suad A. Alshiteewi:** Literature search, data curation, writing—review and editing. All authors read, critically revised, and approved the final version of the manuscript.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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