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Review Article

Advances in Carbon-Based Electrochemical Sensors: A Review on Materials and Future Perspectives

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Abstract — Environmental pollution is a significant challenge to the rise of health risks globally. The electrochemical sensing of hazardous pollutants has emerged as a tool valuable for ecological monitoring due to its cost-effectiveness, high sensitivity, and rapid detection. Carbon-based materials have been studied widely and employed as both electrode materials and due modifiers to their versatility, excellent conductivity, large surface area, and ability to form materials hybrid with polymers, metals, and metal oxide. This review provides an overview of different carbon materials, such as glassy carbon, screen-printed electrodes, carbon nanotubes, and graphene highly their roles in enhancing the sensitivity and selectivity of electrochemical sensors. Additionally, their incorporation of composites hybrids and strategies functionalization is discussed to improve methods sensor performance for real-time in filed applications. Carbon materials' unique properties are essential components in efficient development and reliable sensors for environmental contaminants detection. Future research focuses direction on sustainable practices fabrication, advanced material characterization, and composite innovative designs to address pollutants emerging and extend the applicability of sensors of electrochemical in food safety and healthcare monitoring.

1. Introduction

Environmental contamination is a serious matter that the world is presently with grappling [1]. Consequently, there has been increase noticeable in the number of diagnosed individuals with lifestyle-related diseases like cancer [2]. Key class contaminants of the environment include high heavy metal ions, pesticides, pharmaceuticals, dyes, and personal care products shown in figure 1, [3, 4]. Timely detection pollutants of these are essential for healthy and safe ensuring healthy living, elaborated in figure 2. Among the different techniques available for detecting contamination of environmental, the sensors of electrochemical have significantly reaped attention owing to their deftness of preparation of samples low-priced, portability, and ability to provide rapid analysis of selective [5]. These recognized sensors are for their high selectivity, sensitivity, and specificity, making them higher value to other methods, in terms of sensitivity such as calorimetry [6, 7]. Additionally, electrochemical sensors are the most effective compare techniques like spectroscopic and chromatographic methods. Electrochemical sensors are now in portable advent on a chip has enabled unchanged contaminants of ecological actual samples with significant sensitiveness enhanced [8]. The technique of voltammetric which relies upon variations to produce in voltage a sharp response of current directly corelated with the analyte's concentration, commonly are employed in these sensors. A typical cell of electrochemical contains of a reference, working, and counter electrodes [9]. The electrochemical sensing relies mechanism on the reduction and oxidation of analytes on the working electrode surface [10]. The choice of material for working electrodes plays a crucial role as a modifier in determining the performance of electrochemical sensors. The electrodes used traditionally have largely been supplanted by electrode-based-carbon-material, including electrodes of glassy carbon, screen-printed electrodes, carbon paste electrodes, and laser-induced carbon electrodes. Carbon materials several offer advantages for the applications of electrochemical, such as low-priced an extensive potential series, simple, and comfort of obtainability, them making ideal candidates for use in electrochemical sensors [11].

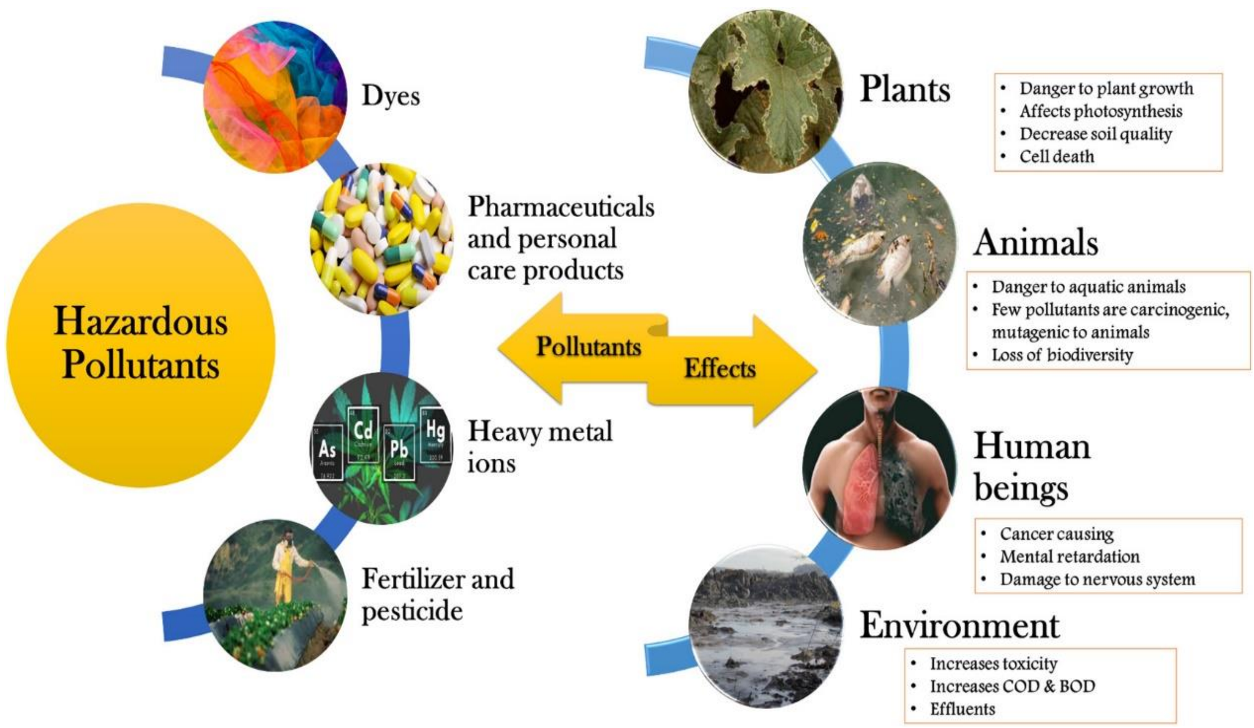

Figure 1. Broad classification and effects of hazardous pollutants; permission from Ref. [3], Copyright, Date; Nov 12, 2024 Licensed Content Publisher Elsevier.

The materials of carbon play a significant part in both modifiers in electrochemical sensors and working electrode materials [12]. Among the different carbon-based electrodes, screen-printed carbon electrodes and glassy-carbon electrodes are the most commonly used for detecting environmental contaminants. As a modifier, a range of porous carbon including carbon materials, quantum-dots, GR-sheets, fullerenes, rGO, GO, CNTs (carbon-nanotubes), graphitic carbon nitrides, (both multiwalled and single), three-dimensional porous carbon, and diamonds, have been successfully employed in sensor fabrication [13-15]. These materials provide active sites and a large surface area for adsorption, which enhances the sensitivity of analyte detection. Pristine carbon materials alone can sufficiently deliver selectivity and sensitivity for sensing applications. Moreover, their capacity to create covalent bind strong with different substances has to led the development of diverse hybrid materials for electrochemical sensing. Often these hybrid materials serve as supports for additional modifier-materials, such as metal-oxides, metals, and polymers that conduct [16]. This brief assessment seeks to address the critical role that materials of carbon-play as both material-modifiers and working electrode components in the detection of dangerous pollutants in the atmosphere by electrolytic means.

1.1. Materials for Carbon Electrodes

The application of carbon as an electrode material dates back to the 19th century when Sir Humphery Davy employed the electrode graphite for alkali metals production [17]. The electrode of caron paste introduced by Adams, R.N. (1958) marked milestone a significant, leading to the adoption widespread of carbon-based electrode materials in the applications of electrochemically [18]. Various carbons have been utilized as materials of electrodes, including highly oriented pyrolytic graphite (HOPG) [19], boron-doped diamond (BDD) [20], carbon fibers (CF) [21], carbon nano-tubes (CNT) [22], carbon paste (CP) [23], glassy carbon (GC) [24], and laser-induced graphene (LIG) [25]. Among these screen-printed carbon electrodes (SPCE), glassy carbon electrodes (GCE), which under fall of the category carbon paste electrodes (CPE), are noteworthy, particularly for their extensive applications in the sensing electrochemical of environmental contaminants figure 3, [26]. This section primarily will focus on SPCE and GCE, highlighting their properties of unique and that make advantages them suitable for detecting a wide range of substances in the monitoring of the environment Table 1.

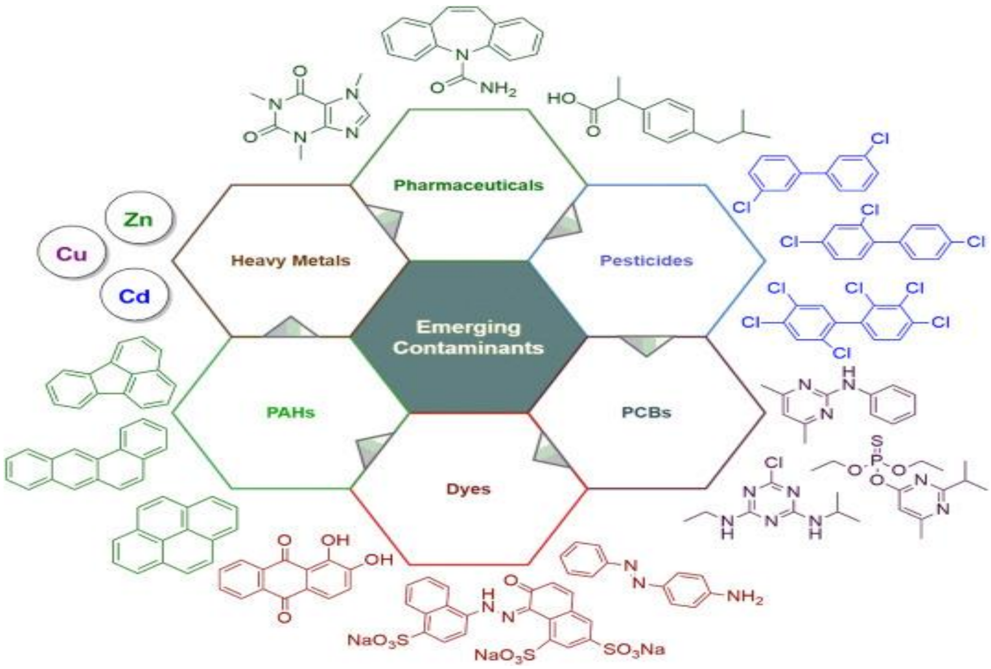

Figure 2. Elsevier (b) Emerging contaminants in the environment; permission from Ref. [4], Copyright, Date; Nov 13, 2024 Licensed Content Publisher Elsevier.

Table 1. Summarizing carbon materials used in the detection of pollutants, their roles, and their data of merit based on literature from 2000 to 2024.

Electrode Carbon Material	Role of Carbon Material	Analyte	Electrochemical Technique	LOD	Linear Range	Ref
Graphene	Conductive platform, signal enhancement	Lead (Pb^{2+})	Differential Pulse Voltammetry (DPV)	0.2 nM	0.5 nM – 100 μM	[27]
Carbon Nanotubes (CNTs)	Electron transport enhancement	Dopamine	Cyclic Voltammetry (CV)	0.5 μM	1 μM – 100 μM	[28]
Graphene Oxide (GO)	Surface area enhancement	Pesticides (carbofuran)	Square Wave Voltammetry (SWV)	1.2 nM	5 nM – 50 μM	[29]
Activated Carbon	Adsorbent, catalytic support	Methylene blue	Amperometry	0.01 μM	0.05 μM – 100 μM	[30]
Carbon Quantum Dots (CQDs)	Fluorescence quenching probe	Chromium (Cr^{6+})	Fluorescence Spectroscopy	10 nM	50 nM – 10 μM	[31]
Carbon Black	Catalyst support	Nitrite	Amperometry	0.05 μM	0.1 μM – 500 μM	[32]
Graphene Nanocomposites	Signal transduction	Organophosphate pesticides	DPV	0.8 nM	1 nM – 10 μM	[33]
Fullerenes (C60)	Signal amplification	Benzene	Electrochemical Impedance Spectroscopy (EIS)	0.5 ppm	0.8 ppm – 50 ppm	[34]
Carbon Dots	Fluorescent probes	Cadmium (Cd^{2+})	Fluorescence Spectroscopy	5 nM	10 nM – 5 μM	[35]
Graphitic Carbon Nitride (g-C_3N_4)	Photocatalyst for degradation	Phenols	Amperometry	0.02 ppm	0.05 ppm – 100 ppm	[36]
Mesoporous Carbon	Catalyst immobilization	Arsenic (As^{3+})	DPV	0.1 μM	0.5 μM – 50 μM	[37]
Reduced Graphene Oxide (rGO)	Signal enhancement	Copper (Cu^{2+})	DPV	0.2 nM	1 nM – 10 μM	[38]
Carbon Nanofibers	Sensing material, high surface area	Bisphenol A (BPA)	CV	0.1 nM	0.5 nM – 50 μM	[39]

1.2. Glassy-Carbon Electrode

Glassy-carbon, also known as different carbon, is extensively utilized in electrochemical-sensing because of its high stability, electrical low resistivity, minimal background current, and corrosion resistance. It is through producing the phenol-formaldehyde resin through carbonization and sp^2 hybridization features carbon atoms in a hexagonal pattern arranged [40]. Diverse forms of glassy carbon, such as cellular glassy carbon (CGC), reticulated-glassy-carbon (RGC), and mono-lithic glassy-carbon (MGC), offer unique properties [41]. RGC with its structure porous and surface area, is effective particularly for electrochemical sensors. The construction of GCE typically incorporates them into insulating tubes, various enabling configurations that enhance mass sensitivity and transport. Pretreatment of GCE includes cyclic voltammetry scans and mechanical polishing to restore electrochemical activity [42]. Surface modification with electrocatalyst nanomaterial enhance the sensors sensitivity and selectivity. For example, GCEs modified with RGO have been used to detect terbutaline with a low detection limit of 0.052 µM. Additionally, a hybrid material of copper oxide and molybdenum (CuO-MoS_2) modified the electrode for carcinogenic detecting sulfamethoxazole (SMX) [43]. Nanorods bimetallic oxide $MnMoO_4$ anchored on nanosheets of graphene facilitated picomolar detection of ornidazole, while polyaniline-Fe_3O_4 nanocomposite achieved a low detection of 0.2 µM limit for 2,4-dichlorophenoxyacetic acid. These highlight modifications to the versatility and effectiveness of GCEs in detecting contaminants hazardous in various applications [44].

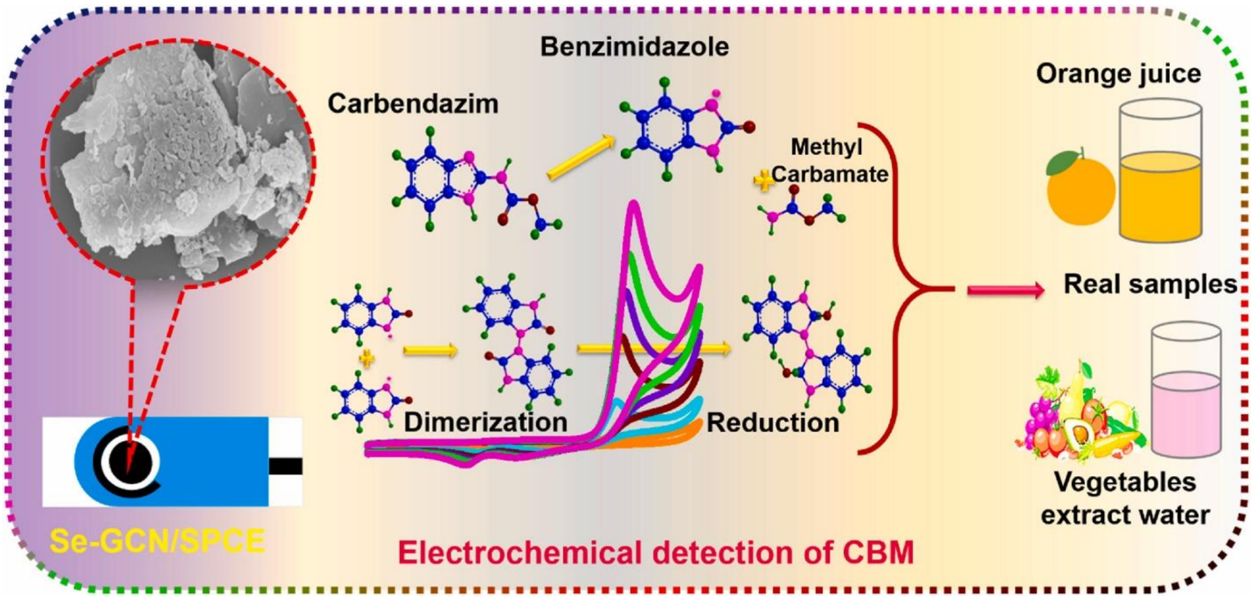

Figure 3. Scheme 1. Electrochemical detection of CBM at Se-GCN/SPCE, permission from Ref. [26], Copyright, Date; Nov 15, 2024 Licensed Content Publisher Elsevier.

1.3. Screen printed Carbon Electrode (SPCE)

Screen-printed electrodes have emerged as an advancement significant in electrochemical sensing, particularly due to portability their compact size, low cost, and disposability [45]. Their nature of disposable eliminates the need for polishing time-consuming processes associated with traditional electrodes like GCEs, enhancing reliability and contamination and minimizing risk during analyte detection. SPCEs effectively can perform qualitative analyses minimally using sample volumes, making them suitable for in-field applications. SPCEs incorporate a conventional system of three electrodes (counter, working, and reference electrodes) onto a single substrate, setup simplifying and enhancing usability. Fabrication involves conducting using nan-ink, which may contain noble metals of nanocomposites, applied like ceramics substrates, filter paper, and PET films [46].

When carbon-based materials are used, the electrodes are to as SPCEs [47]. To improve performance, SPCE can undergo the process of pretreatment, including chemical electro-activation or physical griding. Surface modification nanomaterials with conductive polymers enhance selectivity, sensitivity, and overall efficacy in environmental sensing applications. Notably, noble metals improve the detection limits for various analytes. For instance, an SPCE modified with nanostructures of Ag (silver) was created to enable the simultaneous detection of heavy metals (Pb (lead), Hg (mercury), Cu (copper), and Cd (cadmium) trendy water demonstrating the capacity of noble metal nanostructures to enhance limits of the detection for the pollutants of environmental [48]. Additionally, gold nanospike-modified SPCEs utilized have been for the detection of organophosphate pesticides, dopamine, achieving a sensitivity of 1 nM – 10 µM, 0.8 nM, linear range of 1 µM – 100 and a limit of detection (LOD) of 0.5 µM shown in table 2. Material that are hybrids Mn_3CoO_4 such as multiwalled carbon nanotube composites, have been employed to selectivity antibiotics detect like furazolidone, a yielding 0.5 nM limits of detection [49]. Similarly, nanoparticles of copper selenides aluminum-doped modified SPCEs enabled the detection of L-tyrosine with a limit of 0.04 µM [50]. These highlight advancements in the effectiveness of integrating hybrid nanomaterials and noble metals into SPCEs, enhancing their electrochemical performance and applications, and broadening they are in environmental monitoring and analysis of biochemicals [51].

1.4. Carbon as Electrocatalyst

Electrochemical sensors are increasingly categorized by their element recognition, which includes enzymes, DNA, and electrocatalysts [52]. In the base of electrocatalyst sensors, a layer of coated electrocatalyst is onto the working electrode, surface to mediate the electrochemical reaction [53]. The between the electrocatalyst and analyte facilitates redox reactions, an electrical signal generating used for quantitative and qualitative detection shown in Figure 4 [54].

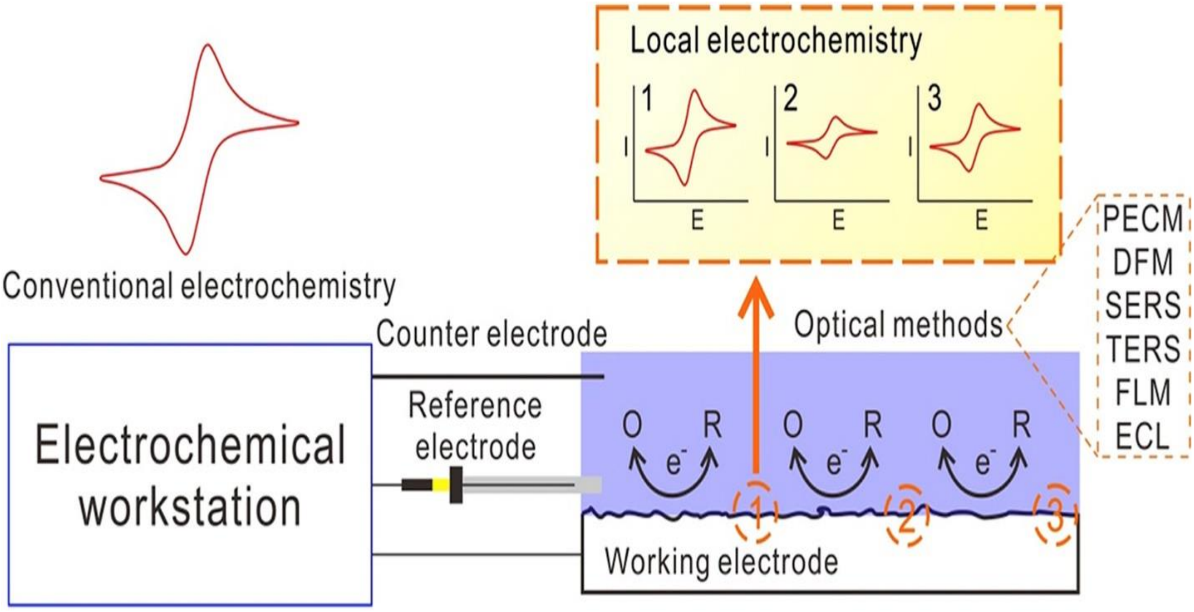

Figure 4. Graphical abstract, electrochemical workstation, permission from Ref. [54], Copyright, Date; Nov 15, 2024 Licensed Content Publisher Elsevier.

Table 2. Recent studies represent innovative applications of carbon materials for electrochemical pollutant detection from 2019–2023.

Electrode Carbon Material	Role of Carbon Material	Analyte	Electrochemical Technique	LOD	Linear Range	Ref
Graphene Nanocomposites	Signal transduction	Organophosphate pesticides	DPV	0.8 nM	1 nM – 10 µM	[55]
Reduced Graphene Oxide (rGO)	Signal enhancement	Copper (Cu^{2+})	DPV	0.2 nM	1 nM – 10 µM	[38, 56]
Carbon Nanotubes (CNTs)	Electron transport enhancement	Dopamine	CV	0.5 µM	1 µM – 100 µM	[57]
Carbon Quantum Dots (CQDs)	Fluorescence quenching probe	Chromium (Cr^{6+})	Fluorescence Spectroscopy	10 nM	50 nM – 10 µM	[58]
Graphitic Carbon Nitride (g-C_3N_4)	Photocatalyst for degradation	Phenols	Amperometry	0.02 ppm	0.05 ppm – 100 ppm	[59]

2. Role of Carbon Materials

Carbon materials are favored electrocatalysts as excellent due to their electrical conductivity, a large area of the surface, and the ability to form covalent strong bonds [60]. They provide for the reaction of multiple active sites of redox reactions significantly enhancing sensor selectivity and sensitivity. Different forms of carbon, including carbon pristine materials like carbon nanotubes and graphene, as well as composites of hybrid, exhibit electrocatalytic remarkable performance. Additionally, carbon electrocatalysts can stabilize materials of the catalytic, such as metal oxides and metal, thereby, improving the sensing efficiency platform [61]. For instance, nanotubes of carbon combined with noble metals hybrid materials create that show superior activity of the catalytic while reducing the number of needed precious metals, making more cost-effective sensors [62]. The tunable properties materials of carbon also allow for the functionalization of surface and interactions optimizing with specific analytes. This modification enhances the activity of electrocatalysts and selectivity for various contaminants in the environment, including organic pollutants and heavy metals elaborated in Table 3 [63]. Overall, carbon materials play a role crucial in electrochemical sensors, selective, sensitive enabling, and detection methods for reliable public health and environmental monitoring.

Table 3. Highlighting recent research on carbon-based materials for pollutant detection, specifically from Pakistan and Turkey.

Electrode Carbon Material	Role of Carbon Material	Analyte	Electrochemical Technique	LOD	Linear Range	Country	Ref
Reduced Graphene Oxide (rGO)	Signal enhancement	Lead (Pb^{2+})	DPV	0.5 nM	1 nM – 10 μM	Pakistan	[64]
Graphene-CNT Composite	Synergistic enhancement	Cadmium (Cd^{2+})	CV	0.1 nM	0.5 nM – 100 μM	Turkey	[65]
Carbon Nanotubes (CNTs)	Electron transport enhancement	Nitrate	Amperometry	0.2 μM	0.5 μM – 50 μM	Pakistan	[66]
Graphitic Carbon Nitride (g-C_3N_4)	Photocatalyst for degradation	Phenol	DPV	0.01 ppm	0.05 ppm – 100 ppm	Turkey	[67]
Carbon Black	Catalyst support	Mercury (Hg^{2+})	Amperometry	0.05 μM	0.1 μM – 500 μM	Pakistan	[68]

2.1. Challenges and Solutions

Despite their advantages, electrodes unmodified often exhibit slow surface kinetics, which selectivity hinders sensitivity for detecting analytes. The bare electrode can have broad peaks produced in electrochemical signals, the differentiation complicating of close compounds related and requiring higher analytes concentrations. To overcome these limitations are essential electrocatalysts for accelerating electrochemical reactions on the surface of the electrode, thus enhancing the kinetics of redox reactions and improving both selectivity and sensitivity [69]. Nanomaterials have prominently become effective electrocatalysts due to their large surface area, superior stability, selectivity, and improved surface kinetics. Commonly used electrocatalysts include metal oxides, metal, and carbon materials, and conducting polymers, each unique advantage contributing [70]. Carbon-based electrocatalysts, like carbon nanotubes and graphene, are notable for their excellent electrical stability and conductivity. Metals such as gold and platinum exhibit high catalytic activity, while metal oxides provide unique behavior of redox and enhanced stability [71]. Offers flexibility of conducting polymers flexibility for functionalization, and further sensor performance.

2.2. Performance Enhancement through Functionalization

Carbon materials functionalized with groups of specific that show high affinity for analytes target enhance the electrochemical of sensors selectivity. For instance, derivatives of graphene-like reduced graphene oxide (rGO) and graphene oxide (GO) are preferred over pure graphene due to their functional group oxygen-containing, which improves interactions with analytes [72]. Functionalized carbon nanotubes (CNTs) also demonstrate sensor response better than CNTs pristine, as these enhance group interaction with analytes, leading to improved selectivity and sensitivity [73].

2.3. Pristine Carbon Materials

Carbon materials also serve as supports excellent for metal catalysts, with metal oxide composites, and conducting hybrids polymer carbon. For example, carbon-metal oxide composites synergistic leverage effect to enhance electron transfer rate and provide active sites for the interaction of analyte [74]. This versatility of carbon material enables advanced technology of electrochemical sensors for sensitive and selective detection of environmental contaminants [27, 75].

2.3.1. Allotropes of Carbon

The unique properties catenation of carbon enables the formation of different allotropes with suitable properties distinct for electrochemical sensing. These include with unique electronic properties of quantum dots and fullerenes all are zero-dimensional (0D) [76]. Multi-walled and single-walled carbon nanotubes, known for conductivity and strength excellent all about the one-dimensional (1D) [77]. Multilayer graphite and graphene sheets are characterized by rapid electron transfer and they are well-known two-dimensional (2D) materials [78]. Diamond and graphite, robust exhibiting physical properties and all three-dimensional (3D) nanomaterials [79]. The morphology of these significant nanomaterials influences the sensitivity of electrochemical sensors. For example, 0D-graphene quantum dots offer high stability and biocompatibility, making them suitable for sensing applications. Carbon nanotubes and graphene enhance electron transfer and adsorption capacity improving sensor performance. The weak van der Waals forces between layers of graphene provide flexibility for sensor design while a high surface area is maintained [80].

3. Applications

Pristine carbon material can effectively as function an electrocatalyst [81]. For instance, electrochemical-rGO used in SPCE achieved limits of detection 0.50 nM for synthetic dyes, the sensitivity showcasing of pristine carbon materials [82]. Similarly, 3D-graphene was effective for the detection simultaneous of uric acid and dopamine with detection limits of 1.27 µM and 0.21 µM, respectively [83]. This example highlights how carbon materials enhance performance sensors across various applications. Additionally, a composite of GO and graphene-upgraded on GCE, achieved of limit of detection of 0.087 µM for the ions of cadmium, demonstrating superior performance due to its specific large surface area and excellent hydrophilicity. A composite of multi-walled carbon nanotubes (MWCNT) and graphene quantum dots also showed the improved response of current for the detection of dopamine, illustrating the advantages of multi-dimensional carbon nanocomposites [84]. Doping can enhance the material of carbon conductivity in materials in electrochemical sensors shown in Table 4. For instance, graphite doped with phosphorus demonstrated a limit of detection of 1 nM in fruit samples for quercetin, highlighting the effectiveness of doping in improving senor performance [85]. For instance, the integration materials of carbon, including their functionalization strategies and diverse allotropes, play a vital role in enhancing the performance of electrochemical sensors. The unique properties and continued versatility drive innovations in the field, contributing to selective and sensitive detection methods for environmental monitoring and beyond.

Table 4. Carbon materials in electrochemical sensing, focusing on their applications, detection limits, and analytes.

Electrode Carbon Material	Role of Carbon Material	Analyte	Electrochemical Technique	LOD	Linear Range	Ref
Graphene	High conductivity, large surface area	Heavy metals (Pb^{2+})	DPV	0.2 nM	0.5 nM – 100 µM	[86]
Carbon Nanotubes (CNTs)	Excellent electron transport	VOCs (volatile organic compounds)	CV	0.1 ppm	0.5 ppm – 50 ppm	[87]
Graphene Oxide (GO)	Enhanced electrode surface	Pesticides (organophosphates)	SWV	1.2 nM	5 nM – 50 µM	[88]
Carbon Quantum Dots (CQDs)	Fluorescence quenching, stability	Heavy metals (Cr^{6+})	Fluorescence Spectroscopy	10 nM	50 nM – 10 µM	[89]
Graphitic Carbon Nitride (g-C_3N_4)	Photocatalytic activity	Organic pollutants	Amperometry	0.02 ppm	0.05 ppm – 100 ppm	[90]

3.1. Metal Carbon Composites

3.1.1. Carbon Support Metals

Carbon material frequently serve as structures support for metals, enhancing the performance and electrochemical sensors sensitivity [91]. For example, palladium-supported porous activated carbon, modified on GCE have been used for the simultaneous of heavy metals ions detection, such as ions of lead 2 plus (Pb^{2+}), and cadmium 2 plus (Cd^{2+}), using square wave anodic stripping voltammetry (SWASV) [92]. The porous structure of carbon activated, with its mesoporous and microporous channels, facilitated deposition striping and mass diffusion process. Meanwhile, the Pd nanoparticles improved conductivity, overall enhancing the performance of sensor. The combined characteristic of Pd, and PAC-nanoparticles resulted in cathodic superior peak currents, compared tom PAC/GCE and bare GCE electrodes [93].

Additionally, core-shell nanoparticles of carboxylated graphene supported Au@Ag) was developed for detection of simultaneous nitrite and iodide, with detection limits of 0.15 µM, and 0.1 µM separately [94]. The combined impact between the Pd nanoparticles and core-shell gold-silver nanoparticles significantly enhanced the sensitivity and how well the electrocatalyst conduct, further boosting sensor performance of these analytes for the detection [95].

3.1.2. Composites of Metallic Oxides and Carbon

Electrochemical sensors make heavy use of metal oxides, because of their high structure stability, low toxicity, sensitivity, and large surface area [96]. They also exhibit rapid adsorption time and adsorption abilities. Simple metal oxides like bimetallic oxide more complexes or ZnO, with spinel or perovskite structures, are commonly employed [97]. Bimetallic oxides are effective particularly due to the presence of cationic interchange and oxygen vacancies, which enhance their sensitivity and electrical conductivity. When combined with materials carbon, which offer a high electrocatalytic activity and large surface area, the effect of synergistic between metal oxides and improve significantly performance of electrochemical [98]. Metal oxide carbon composites are therefore capable of providing shorter response time, better sensitivity, and ranges and enhanced limits of detection. This makes highly effective them in various applications of electrochemical sensing, especially for the detection of environmentally hazardous and contaminants materials.

3.1.3. Simple Metal Oxide Carbon Composites

Composites of metal oxides with materials carbon have shown promise in sensing electrochemical, particularly for detecting toxic pollutants. ZnO@GO composites on GCE demonstrate enhanced antibiotics detection like trimethoprim, and sulfamethoxazole due to their synergistic effect, oxidation peak currents improving and compared to individual components [99]. Similarly, carbon black (CB) has been used for metal support like Fe_2O_3, enhancing the detection in environmental samples of chlorpromazine hydrochloride. The carbon metal oxide composites exhibit large surface area and active sites, which contribute to their superior performance of electrochemical. Notable ternary includes composites, such as CDs/WO_3@GO/GCE, the detection capabilities which improve for creatinine [100]. Bimetal oxides combined with Co_2SnO_4/rGO carbon materials, also enhance sensor performance, allowing for the detection of mesalamine compounds [101].

3.1.4. Carbon Complexes with Conductive Polymers

Conductive polymeric carbon composite materials increase the sensitivity of sensors even more [102]. For example, PEDOT@GR, composite achieved detection simultaneous of multiple analytes, while polypyrrole-GO, composites effectively detected ions of the Cd^{2+} at low concentrations [103]. Combining metal oxides with composites of polymer carbon conducting leads to enhanced electrocatalytic performance, by composites as demonstrated by Fe_3O_4@Ppy/rGO for detection of dopamine and rGO@CNT@Fe_2O_3/polypyrrole for the ions Pb^{2+} achieving impressive detection of limits [104]. In conclusion, the materials of carbon play a crucial role in electrochemical sensor development due to their stability, availability, and diverse forms. Their combination with conducting polymers and metal oxides significantly enhances the selectivity and sensitivity of sensors, making them effective for the detection of environmental pollutants.

4. Key Consideration for Future Research

The advancement of materials based on carbon in electrochemical sensor technology significantly holds potential, driven by continuous composites innovations, methods of sustainable fabrication, and advanced techniques for characterization [105]. One avenue promising is the development of innovative composites that integrate different carbon allotropes with metals, conducting polymers, and metal oxides. Exploring this combination yield can selective sensor and highly selective, enhancing their applicability, monitoring food safety and healthcare in the environment. The shift towards materials of sustainable is also reshaping sensor fabrication approaches. Researchers are focused increasingly on bio-based materials of carbon and green synthesis methods to reduce the impact on the environment. Future research could sustainably prioritize practices without compromising the efficiency of sensors. In this context, advanced techniques for characterization, such as EIS and CV are essential for understanding the property structure relationship of these materials, and the optimization facilitating of sensor performance.

Real-world demand applications of electrochemical sensors that reliably perform in complex matrices such as water, food, and biological samples [106]. Evaluating sensor efficacy under conditions realistic will help translate laboratory-based into insights of practical utility. Additionally, integrating these sensors with technologies emerging, such as artificial intelligence and the Internet of Things (IoT), could enhance processing data and real-time capabilities monitoring, making them more suitable for diverse fields [107]. Optimizing nanocomposites of carbon is also tailoring for critical sensor selectivity and sensitivity. This can be achieved by carefully composition adjusting of carbon materials and interaction their tuning interaction with metals oxides and metals. A focus on analysis morphology, considering factors like size of the particle, surface area, and porosity will allow for the engineering precise of nanocomposites that sensitive maximize to target analytes. Finally, reproducibility and scalability remain crucial for advancing the commercial viability of these sensors. Ensuring that nanocomposites consistently across diverse batches are essential for reliable achieving, widely applicable sensing solutions.

5. Conclusion

By delving deeper into the relationships between morphology, composition, and electrochemical characteristics of carbon-based nanocomposites, researchers and scientists can significantly enhance the efficiency of electrochemical sensors. This review direction holds the develop of potential advanced sensing technologies, that offer sensitivity higher and lower limits detection for environmental pollutants, ultimately contributing to monitoring improved and protection of our environment.

Conflicts of Interest

The authors declare that there is no conflict of interest for this article.

Credit authorship contribution statement

Sajjad Ali Chang (PhD): Writing review, original draft, outlines, future methodology, investigation, and conceptualization. **Aamna Balouch (PhD)**: Writing review, editing and project supervision. **Abdullah (PhD):** Writing review, original draft, outlines, **Haji Muhammad (PhD)**: Grammar correction and editing. **Nihal Deligönül (PhD):** Writing review, editing and project supervision, **Rubab Mansoor (PhD):** Grammar correction and review editing, **Mustafa Tuzen (PhD):** Review, editing and project supervision.

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