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ELECTROCHEMICAL SENSORS FOR DETECTING ENVIRONMENTAL POLLUTANTS - A REVIEW

Andrei-Daniel GEMAN[1, 2], Andreea-Loredana COMĂNESCU[1, 2], Constantin APETREI[1, 2], Cătălina ITICESCU[1, 2], Puiu-Lucian GEORGESCU[1, 2]

[1] "Dunărea de Jos" University of Galați, REXDAN Research Centre,
98 George Coşbuc Blvd, Galaţi, Romania
[2] "Dunărea de Jos" University of Galați, Faculty of Sciences and Environment,
111 Domnească Street, Galaţi, Romania

Corresponding author email: Constantin.Apetrei@ugal.ro

Abstract

Electrochemical sensors are an efficient and versatile tools for monitoring environmental pollutants, providing information on target analytes in a rapid, sensitive and cost-effective manner and representing a good alternative to conventional methods such as spectrophotometry and chromatography in real time or on-site analysis. These sensors use electrochemical methods, including amperometry, voltammetry and potentiometry, to detect a wide range of environmental pollutants, including heavy metals, pesticides and other toxic chemicals, making them well-suited for environmental monitoring. Due to their simplicity, accuracy, low cost and their performance (stability, selectivity, LOD in the micro and nanomolar range) and because they can be modified with nanomaterials, enzymes and molecularly imprinted polymers, sensors and biosensors are increasingly used in environmental monitoring and pollution control. Therefore, this work proposes to present a review of the most recent developments in the detection of environmental pollutants using electrochemical sensors.

Key words: *electrochemical sensor, enzyme, nanomaterial, pollutant.*

INTRODUCTION

Environmental health is important for maintaining life on Earth. Population growth and rapid industrialization have led to gradual environmental pollution, with harmful effects on ecosystems and human health. For this reason, pollution has become a public concern worldwide. Contamination and pollution occur when harmful compounds and pollutants are released into the air, soil, and water, either naturally (through fires or volcanic eruptions) or as a result of human activities. This pollution can have serious effects on human health, causing a range of diseases and conditions, including cancer, respiratory diseases, cardiovascular diseases, and other chronic illnesses. Chemical contaminants, released into the environment as a result of human activities, have become major pollutants that have led to increased toxicity in aquatic ecosystems, soil, and water. Pollution of natural ecosystems can also have consequences for the economy. High costs are incurred in cleaning up polluted areas or mitigating the adverse effects caused by prolonged exposure to a contaminant. High costs are generated by cleaning up polluted areas or mitigating the adverse effects produced by prolonged exposure to a contaminant (Awewomom et al., 2024; Rathod et al., 2024).

Currently, there are numerous methods for detecting and monitoring environmental contaminants. The most common techniques are: chromatographic techniques (liquid chromatography (LC) and gas chromatography (GC) coupled with various types of detection), spectroscopic techniques (atomic absorption spectroscopy (AAS) and ultraviolet-visible spectroscopy (UV-Vis)). Although these methods are effective in detecting compounds of interest, they also have a number of limitations - long sample preparation times, the need for qualified personnel to operate the equipment, the use of toxic solvents, high costs, and the complexity of the equipment. Therefore, it is necessary to use a new alternative that offers significant advantages in terms of cost, sensitivity, and selectivity, as well as in terms of processing time (Wang et al., 2021; Kassim et al., 2022; Dawra & Dabas, 2024; Gątarek et al.,

2025). Sensors and biosensors have become an effective tool for monitoring the environment, water quality, air pollution, soil analysis, and biodiversity conservation. These are widely used as cost-effective, portable, inexpensive, and sensitive analytical techniques that can be combined with other analytical methods to enhance their selectivity and sensitivity. These advantages have led to increased use of these methods in real-time monitoring of environmental pollutants, as a sustainable alternative to traditional methods that does not cause additional pollution (Tajik et al., 2021; Pal et al., 2025).

Pollutants

Substances that cause unwanted changes in the natural environment, with harmful effects on plants, animals and humans, are called pollutants. A compound becomes a pollutant when its concentration exceeds its natural abundance as a result of natural phenomena or caused by human activities (Khasanova et al., 2023).

Classification of pollutants

Pollutants can be classified according to several criteria:

- by nature (microbial or chemical);
- by origin: natural pollutants (which occur naturally but, over time, due to accumulation or a sudden increase in their concentration, exert toxic effects on the environment);
- artificial pollutants (introduced into the environment by humans and their activities);
- based on their elimination in nature in relation to ecosystems, they can be further classified as biodegradable and non-biodegradable pollutants (Khanmohammadi et al., 2020; Ajibade et al., 2021).

Worldwide, the most common pollutants are heavy metals, pesticides and pharmaceutical compounds. These compounds pose a high risk because they can accumulate in the tissues of living organisms, which can lead to the development of degenerative diseases, alter the chemical composition of soil and water (Kordbacheh & Heidari, 2023).

Heavy metals

Heavy metals are a natural component of the environment, but human activities (increased industrialization, exploitation of natural and mineral resources, and economic instability) have disrupted natural geochemical processes, turning this component into a threat to the environment. Their toxic nature, persistence, bioaccumulation, and stability in the environment have come to threaten both natural ecosystems and human health (Ali et al., 2021; Swain, 2024). Heavy metals directly influence the chemical and physical properties of soil, water, and sediment. They can affect the trophic balance in the environment, disrupting the food chain for an indefinite period of time. Sparingly soluble heavy metals can accumulate in excessive amounts and interfere with natural biological processes in living organisms (Ali et al., 2021). Heavy metals can enter water sources in two ways: naturally or artificially. Artificial contamination results from landslides, illegal dumping, and discharges into freshwater or marine habitats, while natural contamination is caused by forest fires, mineral erosion, and volcanic activity (Swain, 2024). Environmental monitoring is important because there is a close link between the pollution of natural ecosystems and human health and socioeconomic development (Huang et al., 2023). Exposure to environmental pollution remains a major risk to human health worldwide. Exposure levels are often uneven and can occur through various pathways (via air or water). The duration of exposure and the concentration of pollutants are increasing year by year. Exposure to multiple pollutants can have adverse effects not only on human health but also on the environment. Thus, environmental monitoring has become one of the most important tasks facing not only the EU but the entire planet (Bălă et al., 2021; Shetty et al., 2023).

Pesticides

Rapid population growth of the current century has led to the growth of the agricultural industry and, consequently, to the widespread use of pesticides. Their use has become widespread because they reduce losses, protect crops, and improve production yields on a global scale. Pesticides are classified according to several criteria: mode of action, chemical class, functional groups, and toxicity. The most important classification criterion is based on the different pest targets: herbicides, insecticides, fungicides, rodenticides, etc. (Tudi et al., 2021).The heavy use of pesticides, such as

chloridazon, methyl parathion and chlorpyrifos, has negative effects on the environment. A large proportion of this end up in the ecosystem, carried either by the wind or by water, with up to 95% of herbicides and over 98% of insecticides becoming pollutants. These pollutants eventually end up in surface and groundwater, lakes, and oceans, where, due to physical and chemical interactions, they can form highly toxic reaction byproducts (Abdollahdokht et al., 2021). Classic pesticides often have high concentrations of organic solvents with low dispersion that remain in soil and sediment for a long time and move in the environment, endangering biological systems (Rad et al., 2022).

Pharmaceutical Products

Of all the emerging pollutants of concern, pharmaceuticals (FP) attract the most attention globally because they cause a high level of environmental pollution (Argaluza et al., 2021). In recent decades, the production and consumption of pharmaceuticals (paracetamol, diclofenac, tetracyclines and azithromycin), have increased rapidly due to declining health, rising food consumption, and advances in medicine (Măghinici et al., 2025). Anti-inflammatory drugs, antibiotics, and analgesics are the most commonly used medications globally and are taken daily around the world. Consequently, water-soluble, pharmacologically active organic micropollutants have begun to enter the environment, causing various harmful effects (Ortúzar et al., 2022; Măghinici et al., 2026). This environmental pollution caused by pharmaceuticals occurs primarily through the discharge of effluents from wastewater treatment plants into surface waters. Urban wastewater contains high levels of compounds resulting from various activities, whether industrial- such as aquaculture and livestock farming - where the use of antibiotics and growth hormones has become common practice, or in human healthcare, where 30-90% of administered oral doses find their way into ecosystems (Zampelli & Verna, 2025). The increasing use of pharmaceuticals to treat, alleviate, or prevent health conditions, as well as their use in veterinary medicine, plays a major role in ecosystem degradation. These pharmaceuticals have toxic effects on ecosystem components, ranging from biota to water and soil quality. These compounds can disrupt the fragile balance of ecosystems, alter the pH of water and soil, and cause genetic changes and malformations in existing biota. In the case of fish, the active compounds in medications cause cellular damage and respiratory problems, with adverse effects on growth, development, and reproductive capacity (Mezzelani & Regoli, 2022; Ortúzar et al., 2022).

Electrochemical methods for detecting environmental pollutants

Contaminants of emerging concern (CECs) continue to threaten the health of natural ecosystems as well as human health, a situation largely attributable to human activities. It is particularly important to monitor ECs, as they tend to migrate from their source and affect various aspects of the environment (sediment, flora, or fauna). Thus, electrochemical (EC) methods are widely used in environmental monitoring, as they are versatile in detecting emerging contaminants (heavy metals, pharmaceuticals, pesticides) (Kumunda et al., 2021; Sivaranjanee et al., 2022). Electrochemical techniques such as voltammetry, amperometry, conductometry, and potentiometry are successfully used today in environmental monitoring for rapid, sensitive detection, as well as for their potential for miniaturization and field deployment (Sivaranjanee et al., 2022).

Sensors can also be classified based on the analysis method they use:

- amperometric sensors - measure current over time based on a constant potential applied to the electrode;
- conductometric sensors - measure a solution's ability to conduct electric current;
- impedance sensors - measure electrical impedance (capacitance and resistance) when a small alternating current is applied;
- potentiometric sensors - used to measure the difference in electric potential between the working electrode and the reference electrode under zero-current conditions;
- voltammetric sensors - measure current based on the variable potential applied to the electrode (Kiaune & Singhasemanon, 2011; Saputra, 2023).

Among voltammetric methods - cyclic voltammetry, square-wave voltammetry, and differential pulse voltammetry - these techniques offer significant advantages such as high precision, simplicity, speed, selectivity, sensitivity, cost-effectiveness, and repeatability (Sivaranjanee et al., 2022). Equally, recent technological advances in the field of nanotechnology (nanofabrication, printing, immobilization) have made it possible to adapt electrochemical sensors for the detection of a wide range of CECs (Hassan et al., 2022). Today, electrochemical sensors have revolutionized environmental monitoring, from water and soil to air quality. An electrochemical sensor is capable of responding continuously, selectively, and reversibly to the presence of a CEC, without disturbing the sample, and of providing accurate, timely information about the ecological status of a specific environment. Sensors consist of two components: a recognition element for the specific or selective binding of the analyte of interest, and a transducer element for transmitting the information. Carbon-based electrochemical sensors (CPE), glassy carbon electrodes (GCE), and screen-printed electrodes (SPE), examples from tables, have proven effective in determining and monitoring CECS in environmental samples. Their performance is determined by response time, signal-to-noise ratio (S/N), sensitivity, selectivity, linear range, and limits of detection (LOD) (Kanoun et al., 2021). Electrochemical sensors convert the chemical signal (the signal generated by the redox reaction occurring at the electrode surface) into a quantifiable electronic signal (Kiaune & Singhasemanon, 2011; Saputra, 2023). Electrochemical sensors can be modified with various materials to improve selectivity and sensitivity toward analytes of interest. Nanomaterials, metal nanoparticles, metal oxides, metal-organic frameworks, molecularly imprinted polymers, and biological elements (enzymes, antibodies, aptamers, DNA, RNA) are the main classes of materials with which electrochemical sensors can be modified to achieve analytical performance (Flores-Contreras et al., 2022; Rafaqat et al., 2022; González-González et al., 2023; Zheng et al., 2024).

MATERIALS AND METHODS

To accomplish this work, articles from the specialized literature were studied and analyzed, from the Google Scholar database (Google Academic), selecting articles published in the last 5 years, between 2022 to the present, focusing on studies related to the configurations of electrochemical sensors used to detect different classes of environmental pollutants. Approximately 20 relevant articles were studied and presented in Tables 1, 2, and 3.

RESULTS AND DISCUSSIONS

Electrochemical sensors based on nanomaterials

Carbon-based nanomaterials (single-walled and multi-walled carbon nanotubes - SWCNT, MWCNT; carbon nanofibers - CNF; graphene quantum dots - GQDs), metallic nanoparticles (AuNPs, AgNPs, PtNPs), metal oxide nanoparticles (ZnO, NiO, Fe_3O_4), as well as polymeric nanomaterials (e.g., chitin nanocrystals - ChNCs) are frequently used as modifier materials for electrochemical sensors and biosensors because they exhibit superior mechanical strength, a high surface-to-volume ratio, enhanced electrocatalytic activity, properties that improve the selectivity and specificity of sensors, as well as response times (Alnahdi et al., 2022; Dinu et al., 2024; Masibi et al., 2025; Fakraoui et al., 2026; Wang et al., 2026).

Electrochemical sensors based on metal-organic structures (MOF)

MOFs are structures formed by inorganic metal ions and organic ligands. MOFs are increasingly used in the modification of commercial electrochemical sensors due to their unique physicochemical properties such as large surface area, high porosity, tunable pore size and high catalytic activity. In recent years, MOFs that have metal ions such as copper, zinc, zirconium and nickel in their structure and carboxylic acid derivatives as organic ligands have been used in the electrochemical detection of environmental pollutants, including active pharmaceutical compounds, pesticides, metal ions, but also phenolic and nitroaromatic compounds (Tajik et al., 2021).

Electrochemical sensors based on molecularly imprinted polymers (MIP)

Molecularly imprinted polymers (MIPs) are polymers obtained by copolymerizing a functional monomer with a cross-linking agent that interacts with the target molecule (template) to form specific binding sites. After the template is removed, these specific binding sites are capable of recognizing and specifically binding the template (Udomsap et al., 2018). MIPs are the subject of intensive research due to their excellent properties, such as the ability to recognize the target analyte in a complex matrix, affordability, ease of synthesis, potential for miniaturization, durability, selectivity, and high physical and chemical stability - characteristics that make them suitable for electrochemical sensor applications in the detection of emerging pollutants, including pesticides and pharmaceuticals in environmental samples (Rao et al., 2018; Udomsap et al., 2018; Thimoonnee et al., 2022; Kamel et al., 2024; Poza-Nogueiras et al., 2026).

Electrochemical sensors based on biological elements

Electrochemical biosensors utilize a wide range of biorecognition elements (enzymes, antibodies, aptamers, DNA, RNA, whole cells) that provide high selectivity and sensitivity in the detection of target analytes. The performance of these electrochemical biosensors depends on the type of electrode, the type of transducer, the biological elements, and the techniques used to immobilize them (encapsulation, adsorption, covalent binding, cross-linking). The advantages of electrochemical biosensors include affordability, simplicity, fast response time, portability, high selectivity, and high sensitivity, making them useful for the detection and monitoring of CECs in environmental samples (Fdez-Sanromán et al., 2025; Hui et al., 2022).

Table 1. Electrochemical sensors for detecting heavy metals in environmental samples

Sensor	Pollutants	Sample	Detection method	LOD	Linear range	Bibliographic reference
SPCE/Fe_3O_4-CNF	Cd^{2+}	River water	SWASV	0.0615 µM	6-80 µM	(Dinu et al., 2024)
	Pb^{2+}			0.0154 µM	14-80 µM	
	Cu^{2+}			0.0320 µM	1-60 µM	
	Hg^{2+}			0.0148 µM	6-80 µM	
SPCE/Fe_3O_4-MWCNT	Cd^{2+}			0.2719 µM	6-70 µM	
	Pb^{2+}			0.3187 µM	14-80 µM	
	Cu^{2+}			1.0436 µM	1-60 µM	
	Hg^{2+}			0.9076 µM	6-80 µM	
Bi-GC/RDE	Cu^{2+}	River water	SWASV	0.0105 µM	0.04-0.35 µM	(Bounegru et al., 2025)
	Pb^{2+}			0.0207 µM		
CNTs/UiO-66-NH_2@AuNPs/GCE	Cd^{2+}	River water	DPSV	0.021 µg/L	0.06-400 µg/L	(Wang et al., 2026)
	Pb^{2+}			0.008 µg/L	0.06-400 µg/L	
PTh/ChNCs/SA/SPCE	Pb^{2+}	Wastewater	SWASV	1.53 nM	10-150 nM	(Fakraoui et al., 2026)

*LOD = limit of detection; SWASV = square wave anodic stripping voltammetry; DPSV = differential pulse stripping voltammetry.

Electrochemical sensors for the detection of heavy metals

Dinu and his colleagues used various nanomaterials (iron oxide nanoparticles (Fe_3O_4 NPs), CNF, and MWCNT), in various combinations, to modify carbon-based electrochemical sensors for the detection of metal ions (Cd^{2+}, Pb^{2+}, Cu^{2+}, and Hg^{2+}) in river water samples. The analytical performance of the SPCE/Fe_3O_4-CNF and SPCE/Fe_3O_4-MWCNT sensors was evaluated using square-wave anodic stripping voltammetry (SWASV), yielding detection limits in the micromolar range. The SPCE/Fe_3O_4-CNF sensor exhibited superior analytical performance in terms of detecting the metal ions of interest, a performance that may be attributed to the CNF structure (thin and long structures) which allows for their homogeneous distribution among the Fe_3O_4 particles, as well as to the synergistic interaction between CNF and Fe_3O_4 (Dinu et al., 2024). In another study, a glassy carbon electrode with a rotating disk modified with a bismuth film (Bi-GC/RDE) was used for the simultaneous detection of Pb^{2+} and Cu^{2+} ions in river water samples, following prior

complexation with EDTA (ethylenediaminetetraacetic acid). The bismuth layer, deposited by electrochemical deposition, ensured the stability and reproducibility of the electrochemical signal in SWASV voltammetric measurements. Bi-GC/RDE exhibited competitive LODs of 0.0207 μM and 0.0105 μM for Pb^{2+} and Cu^{2+}, respectively, detection limits that are significantly more sensitive compared to other RDE sensors reported in the literature for the detection of metal ions (Bounegru et al., 2025). The research conducted by Wang et al. demonstrates that a glassy carbon electrode (GCE) modified with a composite material consisting of modified Zr-MOF structures (UiO-66-NH_2), AuNPs, and CNTs can be successfully used for the simultaneous detection of two heavy metal ions (HMIs), exhibiting remarkable stability and sensitivity, with LODs of 0.021 μg/L for Cd^{2+} and 0.008 μg/L for Pb^{2+}, obtained via DPSV (differential pulse stripping voltammetry) measurements. The sensor exhibited a large surface area and active sites due to the MOF structure, superior conductivity due to CNTs, and localized amplification of surface plasmon resonance due to AuNPs. Analysis of real samples (river water) demonstrated the practical applicability of the CNTs/UiO-66-NH_2@AuNPs/GCE sensor in the detection of environmental pollutants (Wang et al., 2026). As highlighted by Fakraoui and colleagues, the screen-printed carbon electrode (SPCE) modified with colloidally stabilized polythiophene (PTh) nanocomposites containing chitin nanocrystals (ChNCs), using sodium alginate (SA) as the matrix, exhibited excellent electroanalytical performance for the detection of Hg^{2+} and Pb^{2+} ions, with detection limits in the nanomolar range (3.26 nM and 1.53 nM). The novelty of the study lay in the use of a composite consisting of bio-natural polymers with conductive polymers, a composite that reduced the domain size, improved electron transfer kinetics, and prevented aggregation. The excellent results obtained with the PTh/ChNCs/SA/SPCE sensor on real wastewater samples were validated by atomic absorption spectrometry (AAS) (Fakraoui et al., 2026).

Table 2. Electrochemical sensors for detecting pesticides in environmental samples

Sensor	Pollutants	Sample	Detection method	LOD	Linear range	Bibliographic reference
Fe_3O_4 /ITO	chloridazon	Surface water	SWV	0.9 μmol/L	1–22.5 μmol/L	(Alnahdi et al., 2022)
c-MWCNTs@$MoSe_2$-SPCE	methyl parathion	Tap and river water	DPV	2.5 nM	0.008–75 μM	(Beitollahi et al., 2025)
$La_2Sn_2O_7$@GO/GCE	paraoxon ethyl	Soil	DPV	2.73 nM	0.01-360 μM	(Akilarasan et al., 2024)
MSN-PtNPs@d-MIP/SPGE	paraquat	Reservoir and pond water	DPV	3.1 nM	0.025–500 μM	(Thimoonnee et al., 2022)
	glyphosate	Wastewater		4.0 nM		
Cu/Cu_2O/CuO@C/GCE (Cu-BTB MOF)	diflubenzuron	Tap and river water Soil	DPV	130 fM	1.0×10^{-4} M – 1.0×10^{-12} M	(Ji et al., 2023)
AChE/Co-ExZrP/His-GQDs/SPSE	methyl parathion	Groundwater and drinking water	LSV	0.01 μM	0.2–50 μM	(Pengsook et al., 2026)
AChE/CS-GO/GO/CNFs/SPCE	chlorpyrifos	Drinking water	SWV	2.2 nM	2.5 nM–1 μM	(Thet Tun et al., 2023)

*LOD = limit of detection; SWV = square wave voltammetry; DPV = differential pulse voltammetry; LSV = linear sweep voltammetry.

A study reported in the scientific literature demonstrated that the use of Fe_3O_4NPs significantly improves the performance of an indium tin oxide (ITO)-based sensor in detecting chloridazon, an organochlorine pesticide with harmful effects. Electrochemical detection was performed using square-wave voltammetry (SWV), yielding a LOD of 0.9 μmol/L. The Fe_3O_4/ITO sensor exhibited high sensitivity and selectivity, even in the presence of other interferents, when used for the detection of chloridazon in real surface water samples. The high specificity is due to Fe_3O_4 NPs, which can easily bind to the chlorine atoms in organochlorine pesticides (Alnahdi et al., 2023). Beitollahi and his colleagues developed a

screen-printed carbon sensor modified with core-shell nanostructures consisting of MWCNTs functionalized with carboxylic acid (-COOH) and molybdenum diselenide ($MoSe_2$) for the detection of methylparathion (MP) in tap water and river water samples. The DPV technique was used to evaluate the electrochemical response, with the c-MWCNTs@$MoSe_2$/SPCE sensor demonstrating superior analytical performance, characterized by a LOD of 2.5 nM and a wide linear range (0.008–75.0 μM). The performance of this sensor may be due to the synergistic effect between $MoSe_2$ nanostructures, which exhibit high catalytic activity, and MWCNTs, which feature large surface areas with active sites, hydrophilicity, and high electrical conductivity (Beitollahi et al., 2025). In a similar approach, pyrochlore-type lanthanum stannate ($La_2Sn_2O_7$) nanocomposites embedded in graphene oxide (GO) were synthesized and used as modifier materials for the glassy carbon electrode (GCE). Using the DPV technique, the $La_2Sn_2O_7$@GO/GCE sensor demonstrated the ability to detect ethyl paraoxon (POE) in soil samples with a detection limit in the nanomolar range (2.73 nM). The developed sensor showed remarkable results compared to other electrodes (unmodified or modified with other materials), indicating an increase in peak current and a reduction in potential (Akilarasan et al., 2024). A different strategy involves integrating nanomaterials (which provide sensitivity) into molecularly imprinted polymers (which provide selectivity) to detect pesticides in environmental samples. Such an approach was implemented by Thimoonnee and colleagues to detect paraquat (PQ) and glyphosate (GLY) in water samples from reservoirs and ponds, as well as in wastewater. The electrochemical sensor, consisting of a screen-printed graphite electrode (SPGE), modified with a dual-molecularly imprinted polymer (d-MIP), coated on a mesoporous silica-platinum core (MSN-PtNPs), demonstrated excellent detection limits in the nanomolar range (3.1 nM for PQ and 4.0 nM for GLY, respectively). Remarkable results, such as high specificity and selectivity for PQ and GLY, make the MSN-PtNPs@d-MIP/SPGE sensor suitable for on-site water quality monitoring (Thimoonnee et al., 2022). In parallel with approaches based on MIP polymers and nanomaterials, MOF structures were also investigated as modifier materials for the development of electrochemical sensors for pesticide detection. One such study focused on the detection of diflubenzuron, a non-electroactive insecticide from the benzoylurea class, using a Cu/Cu_2O/CuO@C/GCE electrochemical sensor. The electrochemical performance of the developed MOF-based sensor (Cu-BTB MOF) was evaluated using DPV, yielding a very good LOD (in the femtomolar range) and a wide linear range. These significantly improved values may be attributed to the large specific surface area of the octahedral MOF and the active sites of the composite, which enhance electron transfer. The sensor also proved effective on real samples, detecting diflubenzuron in tap water and river water, as well as in soil samples, with good recoveries (Ji et al., 2023). In addition to the materials listed above, researchers have also incorporated biological components - particularly enzymes - as immobilized elements on the surface of the electrodes, with the aim of improving the electrochemical detection of pollutants. A recent study showed that the use of the enzyme acetylcholinesterase (AChE) together with materials such as cobalt-modified exfoliated zirconium phosphate (Co-ExZrP), coated on histidine-functionalized graphene quantum dots (His-GQD) deposited on the surface of a silver screen-printed electrode (SPSE) can sensitively detect methyl parathion (LOD = 0.01 μM) in groundwater and drinking water samples (Pengsook et al., 2026). Another study utilized the immobilization of the AChE enzyme on an SPCE electrode modified with cellulose nanofibers, graphene oxide, and a composite of chitosan and graphene oxide (AChE/CS-GO/GO/CNF/SPCE) to detect chlorpyrifos, an organophosphorus pesticide. The electrochemical performance of the sensor, obtained through SWV measurements, indicated a LOD in the nanomolar range (2.2 nM) and is attributed to the inhibition of AChE's catalytic activity, as well as the use of nanomaterials that significantly improved conductivity (Thet Tun et al., 2023).

Table 3. Electrochemical sensors for detecting pharmaceuticals in environmental samples

Sensor	Pollutants	Sample	Detection method	LOD	Linear range	Bibliographic reference
MIP-EDOT/SPCE	carbamazepine	Tap, river and sea water	DPV	0.58 μM	1-50 μM	(Poza-Nogueiras et al., 2026)
Zr-MOF/GCE	carbamazepine	Groundwater	DPASV	0.0085 μmol·l^{-1}	0.010-0.25 μmol·l^{-1}	(Lalawmpuia et al., 2025)
	ciprofloxacin			0.0062 μmol·l^{-1}	0.01-0.25 μmol·l^{-1}	
ZIF-8/PB/GCE	tetracycline	Lake water	SWV	0.2 pM	1-10^6 pM	(Chen et al., 2026)
TA-Au-Ag-ANpM/Fe-dop-PANI/NiO-NPs/GCE	azithromycin	River and lake water	SWV	0.053 pM	0.8 pM-250 μM	(Adane et al., 2025)
	enrofloxacin			0.013 pM	0.1 pM-550 μM	
NiTe-NPs/GCE	ronidazole	Tap and river water	DPV	1.5 nM	0.01-270 μM	(Barwa et al., 2025)
CNF@Pd-rGO/GCE	rifampicin	Industrial wastewater	DPV	3.3 nM	1-1062 nM	(Devi et al., 2026)
CNF-COOH/SPCE	paracetamol	River water	SWV	0.002 mM	0.0025-0.050 mM	(Fdez-Sanromán et al., 2025)

*LOD = limit of detection; DPV = differential pulse voltammetry; DPASV = Differential Pulse Anodic Stripping Voltammetry; SWV = square wave voltammetry.

Electrochemical sensors for the detection of pharmaceutical compounds

Sensors modified with various nanomaterials have also been developed for the detection of pharmaceutical substances to improve sensitivity and detection times. In a recent study, the use of CNFs functionalized with carboxyl groups (-COOH) for SPCE improved the detection of paracetamol and 4-aminophenol in river water samples. The research highlighted that the carboxyl groups increased the density of active sites on the CNFs, leading to better adsorption of the analytes and improving electron transfer (Fdez-Sanromán et al., 2025). In a similar study, CNFs were used in combination with palladium nanoparticles (Pd NPs) and reduced graphene oxide (rGO) for a GCE to enable ultrasensitive detection of rifampicin, a drug used to treat tuberculosis. The nanomolar LOD, obtained via DPV measurements, indicates that CNF@Pd-rGO/GCE exhibits superior electrocatalytic activity, a performance that can be attributed to the synergistic effects of the nanoparticles used (Devi et al., 2026). Barwa and colleagues also used nanoparticles - this time nickel telluride nanoparticles (NiTe-NPs) - to detect ronidazole (RON), an antibacterial and antiprotozoal drug. Depositing NiTe-NPs onto the GCE surface improved electron transfer, facilitating the reduction of RON. The sensor exhibited a LOD of 1.5 nm, high sensitivity and selectivity even in the presence of other interferents, and was successfully applied for the detection of RON in tap water and river water (Barwa et al., 2025). In addition, two antibiotics, azithromycin (AZM) and enrofloxacin (ENF), were simultaneously detected in environmental samples (river and lake water samples) using a nanomaterial-based electrochemical sensor. The GCE was modified with thermally annealed gold-silver alloy nanocomposites (TA-Au-Ag -ANpM) that improved conductivity, active surface area, and catalytic activity; iron-doped polyaniline (Fe-dop-PANI) that enhanced selectivity by providing binding sites specific to the analytes of interest; and nickel oxide nanoparticles (NiO-NPs) that facilitated electron transfer kinetics. The sensor exhibited LOD in the picomolar range and demonstrated that it is an ideal device for the real-time detection of AZM and ENF in environmental samples (Adane et al., 2025). In parallel with the development of nanomaterial-based sensors for drug detection, researchers have also developed MIP- and MOF-based sensors to overcome the limitations of nanomaterials in terms of selectivity. For example, an SPCE sensor modified with an MIP-EDOT film (obtained by electropolymerization of the functional monomer 3,4-ethylenedioxythiophene in the presence of the target analyte as a template molecule) detected carbamazepine (CBZ) with very high accuracy in tap water, river, and

seawater samples, with recoveries ranging from 82 to 116%. The sensor exhibited superior sensitivity and selectivity for CBZ even in the presence of other interferents (diclofenac, diltiazem, CBZ 10,11-epoxide) (Poza-Nogueiras et al., 2026). Another recent study focused on the development of zirconium-based MOF (Zr-MOF) sensors for the detection of carbamazepine (an antiepileptic) and ciprofloxacin (an antibiotic) residues in groundwater samples. The sensor's improved electrochemical performance is due to the metal-organic framework, which has a large, highly porous surface, making the active surface area of the Zr-MOF/GCE twice as large as that of an unmodified GCE (Lalawmpuia et al., 2025). Another MOF sensor, but this time constructed from an imidazolate zeolite 8 (ZIF-8) structure composed of zinc ions and 2-methylimidazole ligands, onto which Prussian blue (PB) nanoparticles were deposited, successfully detected tetracycline (an antibiotic that can accumulate in aquatic ecosystems). With ZIF-8/PB/GCE, an ultra-low LOD (in the picomolar range), excellent selectivity, and stability were achieved - performance attributed to the synergistic effect between PB, which enhanced electrocatalytic activity, and ZIF-8, which exhibited a large surface area with adjustable porosity, as well as chemical and thermal stability (Chen et al., 2026).

CONCLUSIONS

Environmental pollution is a major problem worldwide. In recent decades, natural ecosystems have been exposed to a range of pollutants that have disrupted their balance. Environmental degradation is largely caused by human activities, which is why constant monitoring of the effects that pollutants have on the environment is necessary. This review provides an overview of the concept of environmental pollution, emerging contaminants (heavy metals, pesticides, pharmaceutical compounds), the environmental components most affected by pollution, and modern methods for monitoring pollutants. Among current methods, electrochemical techniques coupled with new nanotechnologies have attracted global attention due to their promising characteristics. Recent research has shown that the integration of electrochemical sensors with various materials has improved response times, increased the efficiency of detecting analytes of interest in water samples, enhanced the surface-to-volume ratio, boosted electrocatalytic activity, enabled miniaturization, reduced costs, and improved physical and chemical stability, among other benefits.

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