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Nanomaterial-Based Electrochemical Sensing of Heavy Metals in Complex Food Matrices: Challenges from Material Design to Analytical Performance

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Abstract

Food contamination by heavy metals is a major threat to public safety, as these metals tend to bioaccumulate and can cause gastrointestinal, systemic, and neurological disorders. Consequently, there is an increased demand for precise yet accessible and low-cost detection of these hazardous metals in foods. Electrochemical nanosensors have been developed into highly sensitive analytical devices for detecting trace amounts of heavy metals in complex food systems. Recently, integrating nanostructured materials has become increasingly important, as it enhances electrochemical performance by increasing the active surface area, thereby improving electron-transfer kinetics and analyte adsorption at the electrode interface. This review highlights recent developments in nanomaterial-based electrochemical sensors for detecting heavy metals across a wide range of food matrices, including water and beverages, dairy products, seafood, fruits, and vegetables. Emphasis is placed on the use of carbon nanomaterials, metal and metal oxide nanostructures, and hybrid nanocomposites to enhance analytical sensitivity. A relative analysis of reported limits of detection indicates that nanostructured sensing platforms perform well for the analysis of trace levels of heavy metals in food systems. Furthermore, a thorough examination of emerging technologies, including flexible and wearable sensors, AI-assisted sensing, microfluidic approaches, paper-based sensing, and smartphone-integrated sensing, is also presented.

Highlights

• Electrochemical nanomaterial-based sensors for detecting heavy metals in food.

• Integration of nanomaterials enhances selectivity, stability, and detection limits.

• Comparative analysis of sensing platforms and performance metrics is presented.

• Advances in on-site and real-time food safety monitoring.

Novelty Statement

This review consolidates recent advances in electrochemical nanomaterial-based sensors for heavy metal detection in food matrices, covering multiple aspects, including sensing mechanisms, real-sample applicability, and emerging strategies for portable, on-site food safety monitoring.

1. Introduction

Food safety and security are basic and non-negotiable human necessities; heavy metal contamination is one of the global threats to the same. Heavy metals, such as lead, cadmium, mercury, and arsenic, resist environmental degradation and undergo biological magnification across trophic levels, leading to chronic toxicity within ecosystems. These metals react with biomolecules, producing reactive oxygen species, and interfere with cellular processes, leading to severe health problems (Balali-Mood et al., 2021; Liu et al., 2023; Mititelu et al., 2025a). According to the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) (Food and Agriculture Organization DATA, 28/04/2026) in drinking water, contamination by these heavy metals should not exceed the range (heavy metal-specific) of 0.003–0.01mg/L. These contaminants can cause severe health deterioration, involving renal damage, neurotoxicity, carcinogenicity, and congenital anomalies (Mititelu et al., 2025b). The escalating release of toxic heavy metals into the environment through industrial discharges, agricultural practices, and urbanization has led to significant contamination of food systems worldwide (Jaishankar et al., 2014). Mercury is among the most dangerous heavy metals due to its persistence and bioaccumulation potential, as well as its severe toxicological effects on human health (Sankhla et al., 2016; Tchounwou et al., 2012). These metals generally enter the food chain through either contaminated soil, irrigation water, fertilizers, industrial emissions, or atmospheric deposition, and end up in crops, seafood, dairy products, and processed foods, posing serious health risks (Abdelmonem et al., 2025; Awasthi et al., 2026; Satarug et al., 2010). Constant contact with lead, cadmium, and mercury triggers oxidative stress, inflammation, and DNA damage; in even worse cases, these can cause cardiovascular disease and an elevated risk of various cancers (Jomova et al., 2025; Kakimova et al., 2023).

In the wake of this, heavy metal surveillance in food matrices has become a crucial component of global food safety systems and health policies. Traditional methods of analysis, such as Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), and Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES), have long been employed to accurately determine heavy metals in food samples because they are highly sensitive and reliable (Kuswandi et al., 2022). Although these sophisticated analytical methods offer high sensitivity and accuracy, they have drawbacks, including high fixed and operating costs, complex sample preparation, and the need for sophisticated equipment and skilled personnel. Besides, these methods are time-consuming and not well-suited for real-time or on-site analysis, especially for detection in complex food environments, where extensive sample preprocessing is required to remove interference (Verma et al., 2024).

As a result, alternative sensing strategies have been employed, making electrochemical sensors promising due to their low cost, portability, rapid response, and on-site decision-making capabilities. Additionally, properties such as sensitivity and selectivity can be enhanced by incorporating nanomaterials, making them a better choice for detecting heavy metals along the food chain. Figure 1 shows the evolution of technologies for detecting heavy metals in food matrices.

Nanotechnology has revolutionized sensor development, enabling diverse structures and properties, thereby improving the sensitivity, miniaturization, and portability of analytical systems and enabling efficient identification of contaminants in complex food matrices. Electrochemical nanosensors have been used as promising diagnostic devices for detecting heavy metals due to their low detection limits, selectivity, repeatability, and fast response times, among other advantages, as well as their feasibility for miniaturization into portable devices (Ariño et al., 2022a; Naresh & Lee, 2021). Electrochemical detection

techniques, involving anodic stripping voltammetry, differential pulse voltammetry, and square wave voltammetry, enable accurate determination of trace metal ions by altering electrical signals at deformed electrode surfaces (Sulthana et al., 2024). The use of nanomaterials, including metal nanoparticles, metal oxide nanostructures, carbon nanotubes, graphene, and their nanocomposites, has greatly improved the analytical performance of electrochemical sensors by offering increased active surface area, enhancing electron-transfer kinetics, and providing selective binding between metal ions (Y. Zhang et al., 2025).

A plethora of review articles in recent years have drawn significant attention to electrochemical sensors for heavy-metal detection in food matrices, primarily due to their selectivity, sensitivity, cost-effectiveness, and rapid response. Reviews by Meng et al.(Meng et al., 2023a), Shan et al.(Shan et al., 2026), Sakthivel et al.(Sakthivel et al., 2024), Shi et al.(Shi et al., 2023), Alughare et al. (Alughare et al., 2026), Anchidin-Norocel et al.(Anchidin-Norocel et al., 2024), have discretely discussed nanomaterial-based electrochemical sensing, electrode modification, food safety implications, and food matrix effects. However, these reviews have mainly focused on sensing materials or analytical methodologies or have summarized application-oriented studies. Compared to this, our review article uniquely integrates these viewpoints by critically relating nanomaterial properties, electrochemical sensing mechanisms, analytical performance, and applicability in complex food matrices, as well as emerging approaches for multiplex metal detection, and the development of portable electrochemical sensors, thereby providing a comprehensive and holistic understanding of the field. Following this, it moves beyond descriptive summarization by incorporating a critical comparative framework to evaluate the practical viability of nanomaterial-enabled electrochemical sensing platforms. Uniquely, the concluding section succinctly highlights the major challenges and limitations of electrochemical sensing strategies for detecting heavy metals in complex food matrices, while also discussing the potential future perspective to enhance sensitivity, selectivity, and real-world applicability for food safety monitoring through the integration of next-generation sensing techniques.

2. Fundamentals of Electrochemical Nanosensors

Electrochemical nanosensors are analytical devices that use nanomaterials to transduce a target analyte (e.g., a heavy metal ion) into an electrical signal. According to Vogel et al.(Vogel, 2019), a nanosensor is any nanodevice that responds to physical or chemical stimuli and converts them into measurable signals. In practice, an electrochemical nanosensor is a combination of a given recognition element (a chelating ligand, polymer film, or ionophore) to bind the metal ion, a nanostructured transducer (the electrode surface), and typically a signal amplification scheme (e.g., catalytic labels or multi-electron redox cycles). When the heavy-metal ion is bound or redoxed on the working electrode, an electrical signal (current, potential, or impedance) is produced proportionate to the concentration of the analyte (X. Wang et al., 2022). Electrochemical nanosensors are particularly useful for detecting heavy metals, as traditional techniques (e.g., AAS, ICP-MS) are too costly and time-intensive and require complex equipment (Sharma et al., 2021) methods can be swift, inexpensive, and field-deployable (Chatziathanasiou et al., 2024; Waheed et al., 2018). Voltammetric techniques are favored for trace metal analysis because of their low cost, simplicity, ease of operation, rapid analysis, portability, sensitivity, and selectivity. As Waheed et al.(Waheed et al., 2018) note, modifying an electrode with nanomaterials (carbon nanotubes, graphene, metal nanoparticles, etc.) increases catalytic activity and conductivity, provides a large active surface area, and enhances electrode kinetics, greatly improving sensitivity. Likewise, highly conductive carbon nanomaterials or metal nanofilms can serve as electron mediators or preconcentrates to further boost the signal (Stambouli et al., 2026).

2.1 Architecture of Electrochemical Sensors

Typical electrochemical sensors use a three-electrode system: a Working Electrode (WE), a Reference Electrode (RE), and a Counter (auxiliary) Electrode (CE). The WE is the sensing surface (often a glassy carbon, Au, Bi, or carbon nanotube film) onto which the recognition element (e.g., a coordinating polymer, enzyme, or DNAzyme) is immobilized, as depicted in Fig. 2. The RE (often Ag/AgCl) maintains a stable reference potential, while the CE completes the circuit. Stambouli et al. (Stambouli et al., 2026) emphasize that the reference electrode provides a stable potential to which the other potentials can be referenced and that a redox reaction occurs at the surface of the working electrode (WE), inducing a charge transfer between the analyte and electrode (Chatziathanasiou et al., 2024). In other words, when a metal ion is reduced or oxidized at the WE, a quantifiable current or voltage change is produced. Nanomaterials are integrated by modifying the electrode surface with carbon nanotubes (CNTs), graphene sheets, or metal-oxide nanoparticles, which can be drop-cast or electrodeposited onto the WE. These nanostructures drastically enlarge the effective surface area and introduce catalytic sites. As Stambouli et al. (Stambouli et al., 2026) note, incorporating CNTs, graphene, or AuNPs enhances the sensitivity, conductivity, and electrocatalytic activity properties of the working electrode, enabling highly developed conductive surfaces with high densities of immobilized bioreceptor molecules. Waheed et al. (Waheed et al., 2018) similarly report that nanomaterial modifications lead to increased catalytic activity, enhanced conductivity, a large active surface area, and fast electrode kinetics. The result is a much larger current response per bound ion. In addition to physical deposition, nanomaterials can be covalently bonded or entangled with polymers on the electrode, and functional groups (e.g., thiols, carboxyls) are often used to attach recognition ligands. In sum, nanomaterial functionalization and electrode modification create a 3D porous network that improves electron transfer and sensitivity compared to a bare electrode (X. Wang et al., 2022).

2.2 Electrochemical Detection Techniques

Several voltammetric techniques are used to detect heavy metals at modified electrodes. Cyclic voltammetry (CV) sweeps the potential of the WE linearly forward and backward while measuring current. CV provides qualitative information on redox potential and kinetics, but its sensitivity is limited by capacitive charging currents, resulting in detection limits typically in the micromolar range. Square-Wave Voltammetry (SWV) and Differential Pulse Voltammetry (DPV) are pulse techniques that greatly improve sensitivity. In DPV, small voltage pulses are superimposed on a staircase ramp, and the current difference is measured, which largely cancels the charging current (Chatziathanasiou et al., 2024; X. Wang et al., 2022). In SWV, symmetric square-wave pulses are applied, and current is sampled at each pulse's end. Both methods yield sharp peaks and can detect concentrations as low as μM–nM. Indeed, SWV and DPV yielded remarkable results, with low detection limits consistent with health assurance standards. These pulse methods are also faster than CV, and SWV is well-suited to simultaneous multi-metal assays (recording forward and reverse pulses) (Zhao et al., 2022). Anodic Stripping Voltammetry (ASV) is

especially popular for trace metals. In ASV, metal ions in the sample are first preconcentrated onto the WE (often as a metal film or amalgam) under a fixed potential, and then the potential is swept positively to oxidize (strip) the metals from the WE. Each metal produces a distinct stripping peak. This preconcentration step yields extremely high sensitivity (often ng/L or sub-ppb), surpassing simple voltammetry. Zhao et al. (Zhao et al., 2022) achieved limits of detection of 2.4 µg/L for As(III), 1.2 µg/L for Pb(II), and 0.8 µg/L for Cd(II) using a nanocomposite-modified ASV sensor. Practically, ASV can achieve ng/L (ppt) levels in clean samples and thus becomes the gold standard for the analysis of trace heavy metals. There are trade-offs to each technique. The preconcentration step enables ASV to achieve extremely low limits of detection for trace metals (usually ng/L to low µg/L). DPV and SWV are highly sensitive (typically low-µM or nM) and relatively fast as well. CV is best when mechanical studies (e.g., verification of redox potentials, surface reactions) are required. Still, it has a higher noise level and a higher limit of detection than pulse techniques. All these techniques utilize enhanced signals from the nanomaterial-modified electrodes. According to Wang et al. (X. Wang et al., 2022)EC biosensor techniques (CV, SWV, and DPV) are the most widely used because they convert binding events into currents or potentials that can be easily measured. Sensors such as nanomaterials are highly selective and sensitive, with fast response times, compatible with complex samples, and inexpensive, which is why they are the most appropriate biosensor technology for detecting heavy metals in food matrices (Chatziathanasiou et al., 2024; Zhao et al., 2022). Table 1 briefly compares the electrochemical techniques used in sensors for detecting heavy metals.

Table 1
Comparison of electrochemical techniques for nanosensor-based heavy-metal detection.

Technique	Advantages	Limitations	Applications	References
SWV	Very fast scan, high sensitivity, can multiplex	Requires optimization of frequency/pulse	Multi-metal detection, field assays	(X. Wang et al., 2022)
DPV	High sensitivity, suppressed background current	Slightly more complex waveform	Trace metal ions in liquid samples	(Chatziathanasiou et al., 2024)
CV	Good for mechanism and electrode characterization	Lower sensitivity (high background current)	Sensor development and fundamental redox studies	(Waheed et al., 2018)
ASV	Extremely sensitive, element-selective	Requires preconcentration, electrode cleaning; potential interferences	Trace metals (Pb, Cd, Hg, As) in water/food	(Zhao et al., 2022)

3. Nanostructured Electrochemical Platforms for Heavy Metal Detection in Food

Nanostructured platforms have revolutionized heavy-metal sensing in food matrices. Nanomaterials enable unprecedented electrochemical performance by significantly enhancing the electrode's active surface area, introducing catalytic sites for redox reactions, and forming highly conductive electron-transfer pathways. In practice, nanomaterial modification of a carbon electrode increases the number of adsorption sites for metal ions, enhances charge-transfer kinetics, and provides inherent signal amplification (e.g., through catalytic cycles), thereby reducing the detection limit by orders of magnitude (Waheed et al., 2018). Two-dimensional graphene and graphene oxide (reduced graphene oxide), for instance, are truly fantastic examples in this regard; both have very large surface areas and extended π-conjugation, which facilitate conductivity and electron flow. It translates to higher sensitivity and faster sensor response; graphitic substances have enabled sub-ppb detection of Pb^{2+} and Cd^{2+} in water and food extracts (Saqib et al., 2025). Nanomaterials tend to be intrinsically catalytic: noble metal NPs and certain metal oxides can catalyze the oxidation or reduction of metal analytes, thereby enhancing the current signal. As a result, modern electrochemical sensors report detection limits for key contaminants (Pb^{2+}, Cd^{2+}, Hg^{2+}, As^{3+}) in food well below regulatory levels. These gains are why nanostructured platforms serve as the foundation for high-performance sensors in food safety monitoring.

3.1 Carbon-Based Nanomaterial Sensors

Carbon nanomaterials, especially graphene, graphene oxide (GO), and carbon nanotubes (CNTs), are ubiquitous in electrochemical heavy-metal sensors. Graphene (GR) is a one-atom-thick sheet of sp^2 carbon with an enormous specific surface area. Its derivatives, GO and rGO, carry oxygen-containing functional groups that allow facile chemical modification and ion adsorption. These carbon materials dramatically improve electrode performance. Lawal A. et al. (Lawal, 2019) report that graphene-based electrodes exhibit higher sensitivity and lower detection thresholds compared to traditional carbon materials. Graphene and CNTs have exceptionally high conductivity, which enhances electron-transfer rates in voltammetry, thereby amplifying signal strength at a given analyte concentration. Meanwhile, their large surface area provides a dense number of active sites: heavy metal ions such as Pb^{2+} or Cd^{2+} may adsorb on the carbon surface (which is often catalyzed by surface oxygen groups or surface-attached ligands), enhancing the effective preconcentration in methods such as anodic stripping voltammetry (ASV) (Dorozhko et al., 2021).

These benefits can be depicted by many examples. In another study, Peng et al.(Peng et al., 2023) developed a 3D graphene aerogel functionalized with Au nanoparticles and a Hg^{2+} detection DNA aptamer; the porous structure of the graphene macro lattice gave a large active surface, whereas the AuNPs and the DNA aptamer were used to improve the binding and electron transfer, with an astoundingly low LOD (0.16 fM in milk). Similarly, a gold nanoparticle-graphene hybrid film was reported to detect Hg^{2+} at 6 ppm, well below WHO limits (Gong et al., 2010a). The graphene backbone in both sensors was essential: it provided high conductivity and numerous adsorption sites, whereas the metal NPs provided catalytic activity.

The same applies to carbon nanotubes (CNT). Their tubular sp^2 structure enables rapid electron transport along the tube, and multidimensional CNT networks can form a porous, conductive film on the electrode. CNT-modified electrodes have been widely explored for the electrochemical detection of Cd^{2+} and Pb^{2+} owing to their enhanced surface area and conductivity. Priya et al. (Priya et al., 2020) described the functionalization of biomolecules such as L-cysteine (L-Cys) and L-serine with hyaluronic acid, which significantly improved the metal-ion affinity and sensing performance (Fig. 3a and b). L-Cys-modified electrodes exhibit sensitivities of 0.7 µA/nM for Cd^{2+} and 3.5 µA/nM for Pb^{2+}, while L-Cys/MWCNT composites show sensitivities of 0.6 µA/nM and

2.6 μA/nM, respectively. The sensors were fabricated by drop-casting onto glassy carbon electrodes, having an operational linear range of 0.4–4 μM and achieved low detection limits of 0.032 μM (Cd^{2+}) and 0.015 μM (Pb^{2+}) for L-Cys, and 0.057 μM (Cd^{2+}) and 0.034 μM (Pb^{2+}) for L-serine, as seen in Fig. 3d and e, hence suggesting their applicability for trace-level heavy metal detection in food samples. Correspondingly, Martinez Jimenez et al. (Martinez Jimenez et al., 2021) synthesized (Polyethyleneimine) PEI-functionalized CNT/graphene oxide (PEI-CNT/GO) layer-by-layer sensor on gold interdigitated electrodes that exhibited higher sensitive detection of Pb^{2+} in aqueous media. Their sensor showed a detection limit as low as 36 pmol/L and a sensitivity of 4.3 μA/μmol, which is attributed to strong metal-ion interactions with functional groups in the nanocomposite (Fig. 3c and f). Hence, based on their study, it can be concluded that resistive electrochemical sensors are potential platforms for trace-level Pb^{2+} monitoring in water systems. In all cases, the use of carbon nanomaterials yields electrodes with fast charge transfer and high electroactive surface area, which in turn produces strong stripping peaks in ASV or sharp signals in DPV/SWV for trace heavy metals.

Analytical techniques used on carbon-based platforms are typically ASV (due to its high sensitivity) and pulse voltammetry (DPV, SWV), both of which offer superior signal-to-noise ratios. For instance, DPV on a graphene oxide–modified electrode can resolve Pb^{2+} and Cd^{2+} peaks at concentrations in the μg/L range. SWV is also popular for its speed: graphene-enhanced SWV sensors have achieved multi-ion detection (Pb^{2+}, Cd^{2+}, Hg^{2+}) in a single scan. Importantly, these carbon nanoplatforms have been demonstrated in actual food matrices, e.g., fish tissue digests, milk samples, and fruit juice, usually with recoveries exceeding 90%. This shows that the high sensitivity provided by carbon nanomaterials is resistant to the complex sample conditions (Saqib et al., 2025).

3.2 Metal and Metal Oxide Nanomaterial Sensors

Metal and metal oxides are another class of nanomaterials used in electrochemical sensors. Nanoparticles (NPs) of noble metals such as gold (AuNPs) and silver (AgNPs) are often incorporated into carbon platforms or sprayed onto electrodes. AuNPs provide good conductivity and catalytic surfaces that reduce the overpotential of metal oxidation. To illustrate, when using AuNP-modified electrodes, Hg^{2+} and Cd^{2+} are oxidized at more negative potentials, resulting in larger stripping peaks (Gong et al., 2010a). Graphene quantum dot–AuNP conjugates have demonstrated high sensitivity toward heavy metal ions such as Hg^{2+} and Cu^{2+}, achieving ultralow detection limits of 0.02 nM and 0.05 nM, respectively, along with sensitivities of 2.47 μA/nM (Hg^{2+}) and 3.69 μA/nM (Cu^{2+}) (Ting et al., 2015). However, despite these impressive analytical performances under controlled conditions, the practical applicability of such nanostructured systems remains dependent on factors such as nanocomposite stability, reproducibility of synthesis, and susceptibility to interference from complex sample matrices, which may affect their reliability in real-world food and environmental monitoring (Neethirajan et al., 2018). Similarly, AgNP-based systems improve sensitivity by forming alloys or intermetallics with metals such as Cd or Zn during preconcentration. Still, issues such as poor long-term stability and susceptibility to oxidation can limit reproducibility and practical applicability (Ambrusi et al., 2014; Tamilselvan et al., 2022).

The integration of metal oxides with nanostructured electrodes has attracted significant attention to overcome the limitations of conventional materials, offering enhanced electrocatalytic activity and improved detection of heavy metal ions. Zinc oxide (ZnO) and titanium dioxide (TiO_2) nanostructures are nontoxic and stable materials that can be prepared with high surface areas (e.g., nanorods, nanoflowers) (Agarwal et al., 2019). ZnO contains a conduction band capable of electron transfer, and cations can be adsorbed to the surface of ZnO. ZnO nanostructure-modified electrodes are typically more sensitive to Pb^{2+} and Cd^{2+} (a ZnO nanorod array was used to detect Pb^{2+} at approximately 0.1 μg/L by ASV, as expected) (Sledevskis et al., 2025). Similarly, Ganesamurthi et al. (Ganesamurthi et al., 2022) evaluated the electrochemical performance of vitamin B_2 (riboflavin) using binary metal oxide core-shell structures of ZnO and MnO. A simple hydrothermal synthesis route formed the ZnO as the core and MnO as the shell. The sensor exhibited a wide linear range with LOD of 13 nM and sensitivity of 0.3746 μA μM^{-1} cm^{-2}. This performance could be attributed to the synergistic effect of ZnO and MnO, driven by increased active sites resulting from their high surface areas and morphologies. The authors further validated their sensor by testing 3 different samples, for example, blood serum, urine, and spinach containing riboflavin. Iron oxide (Fe_3O_4) nanoparticles confer magnetic functionality: they can be preconcentrated in a magnetic field to attract metal ions from solution, and then liberated at the electrode, enhancing sensitivity. Moreover, the Fe(II)/Fe(III) redox couple can facilitate charge transfer. In fact, a composite of Fe_3O_4 and graphene was found to be an “optimum” platform for simultaneous Pb^{2+}/Cd^{2+} detection in food samples (Jjagwe et al., 2024; Meng et al., 2023b).

Thus, metal and metal oxide nanomaterials improve electrochemical sensing by acting as excellent catalysts and conductive bridges. This is mainly achieved through their size-dependent properties and high electrical conductivity, which lowers resistance at the electrode interface and thereby improves the signal-to-background ratio. The current generated per ion increases, thereby enabling a lower detectable concentration of target analyte. For instance, Bi_2O_3 nanoparticles are often used to form “bismuth-film electrodes” that mimic mercury electrodes without toxicity, yielding very low LODs for Pb^{2+}/Cd^{2+} in beverages (Zhu et al., 2014). In food applications, Au- or Ag-modified electrodes have successfully detected Pb^{2+}, Cd^{2+}, and Hg^{2+} in milk, vegetable extracts, and grains, with limits of detection as low as μg/L or ng/L (Pan et al., 2024). An AuNP-modified screen-printed electrode was used to measure Pb^{2+} in river water with an LOD of 0.082 μg/mL (Samira Ashour B. Shoub, 2017). These examples underscore that metal oxide nanostructures can dramatically enhance the sensitivity and selectivity of heavy-metal assays in food samples.

3.3 Hybrid and Other Nanomaterial Composites

The construction of hybrid nanocomposites enables synergistic interactions, as combining different materials often yields enhanced physicochemical and electrochemical properties compared to the individual components. For example, hybrid graphene–nanoparticle (NP) composites are the most widely explored category because the sp^2-hybridized carbon structure of graphene serves as a highly stable, large-surface-area framework. In contrast, metal nanoparticles act as catalytic centers and active binding sites, collectively enhancing electrochemical sensing performance. A sensor with cobalt-based metal-organic framework (MOF) particles anchored by AuNPs (Co-MOF) on a carbon electrode was used to simultaneously detect Pb^{2+} and Cd^{2+} in drinks and cereals with LODs of 0.07–0.011 ng/mL. In this case, the MOF's porous structure was pre-concentrated. The ions provided coordination sites, and the AuNPs hastened electron transfer (Pang et al., 2023). In another study, Lin He et al. [43] used vertically aligned graphene electrodes decorated with bismuth nanoparticles (BiNPs) that showed improved electrochemical performance towards Pb^{2+}, and this could be possible because of the smaller particle size (~

4.6 nm) of bismuth, hence providing a larger surface area, enhancing faster electron transfer. The optimized sensor with screen-printed electrode achieved a wide linear range of 5–200 µg/L and a low detection limit of 0.15 µg/L. The sensor was further validated with real water samples, demonstrating good selectivity and repeatability, highlighting the importance of metal nanoparticle-graphene hybrids in sensing platforms.

Nanoparticle-polymer hybrids are another class of nanomaterials being explored for electrochemical sensing. The benefit of this synergy is that, individually, nanoparticles tend to aggregate due to their high surface energy, which can be prevented by the polymer matrix. In addition, the polymer's soft nature can be enhanced by incorporating nanoparticles to improve mechanical stability. Thus, it can be concluded that embedding nanoparticles into an ion-permeable matrix creates highly efficient interfaces (Ali et al., 2025; Hira et al., 2021; Rahman et al., 2025; Terán-Alcocer et al., 2021). For example, Jassem Wannassi et al.(Wannassi et al., 2023) synthesized a conductive HKUST-1@PANI composite to enhance surface area and conductivity by polymerizing polyaniline within the microporous Cu-BTC (HKUST-1). This combination enabled sensitive Pb^{2+} detection using DPV, with a wide linear range (0.005–50 µM) and a low detection limit of 5 nM. The sensor also demonstrated good selectivity towards interfering ions, highlighting the potential of MOF–polymer composites for electrochemical sensing. Similarly, a conductive PANI@Bi-MOF composite was fabricated via in situ polymerization of polyaniline on a bismuth-based metal–organic framework and further evaluated using differential pulse anodic stripping voltammetry (DPASV) (Fig. 4(a) - (c)). The sensor exhibited a low detection limit of 0.0108 µg/L and a wide linear range (0.025–20 µg/L) for Pb^{2+} detection. Further, the sensor was validated with real water samples, demonstrating outstanding performance and underscoring the potential of MOF–polymer hybrids for heavy-metal sensing (Saleem et al., 2025).

Metal–organic frameworks (MOFs) have attracted significant attention because of their highly porous and crystalline nature, composed of metal nodes and organic linkers, which is ideal for electrochemical sensing, as these facilitate analyte adsorption and chelation (Hu et al., 2026; Muthukumaran et al., 2025). Despite these advantages, MOFs inherently suffer from low conductivity, necessitating integration of a cocatalyst to optimize their sensing capabilities (Kajal et al., 2022; M. Yang et al., 2024). For instance, Zr-MOF-based electrochemical platform incorporating methylene blue demonstrated highly sensitive, rapid detection of multiple heavy metal ions (Cd^{2+}, Hg^{2+}, Pb^{2+}, and As^{3+}) in milk, achieving sub-ppb detection limits and successfully applied to real samples, thereby highlighting the potential of MOFs for on-site food safety monitoring (Xiong et al., 2023). Other MOF-based systems used to detect heavy metal ions include zeolitic imidazolate frameworks (ZIFs), which have been combined with conductive substrates (Zhou et al., 2025). Chen et al. (X. Chen et al., 2023) fabricated an electrochemical sensor based on amine-functionalized ZIF-8, which was further enhanced by the incorporation of carbon nanotube via electrostatic assembly with ultrasonic assistance and in situ deposition of bismuth films. The proposed sensor, tested for simultaneous detection of Pb^{2+} and Cd^{2+} ions in water, showed linear ranges of 0.050–1.000 µM (Pb^{2+}) and 0.100–0.700 µM (Cd^{2+}), with lower detection limits of 8 nM (Pb^{2+}) and 12 nM (Cd^{2+}) (Fig. 4(d) - (f)).

Overall, the above studies conclude that hybrid nanostructures improve the performance of electrochemical sensors by increasing sensitivity and boosting response through enhanced chemical interactions and electron transfer. They also improve sensor stability by preventing nanoparticle aggregation. Notably, these hybrid systems facilitate multi-metal detection, as different functional components can interact selectively with various ions, enabling simultaneous analysis based on distinct electrochemical signatures (e.g., Pb^{2+} and Cd^{2+} at different redox potentials). This results in faster and more accurate food safety testing tools while requiring less sample preparation (Chu et al., 2019; Fu et al., 2018; Qin et al., 2023).

4. Electrochemical Nanosensors for Heavy Metal Detection in Food Matrices

Heavy metal contamination across diverse food matrices, including water, dairy products, seafood, and plant-based foods, poses significant risks to human health and necessitates reliable monitoring strategies. Electrochemical nanosensors have emerged as effective tools for this purpose, owing to their high sensitivity, rapid response, and ability to operate in complex sample matrices. Incorporating nanomaterials enhances electron transfer, increases active surface area, and improves analyte selectivity, making these sensors particularly suitable for real-world food analysis. This section highlights recent advances in electrochemical sensors for heavy metal detection across different food matrices, with a specific focus on water, dairy products, seafood, fruits, and vegetables. Each subsection provides a comparative food-wise review of sensor advancements, including their analytical performance and application scope, which is also tabulated for easy referencing.

4.1 Review of nanosensors for heavy metals in water

Electrochemical nanosensors have been extensively developed for detecting heavy metal ions in water matrices, owing to the relatively low matrix complexity compared with other food systems. Water samples generally contain fewer organic compounds, proteins, and lipids that may interfere with electrochemical measurements, thereby enabling efficient adsorption of metal ions onto nanostructured electrode surfaces and improved electron transfer during electrochemical detection. As a result, numerous nanomaterial-based electrochemical sensing platforms have demonstrated excellent analytical performance for trace metal detection in environmental and drinking water samples. Table 2 summarizes various electrochemical nanosensor platforms developed for the analysis of water samples.

Carbon-based nanomaterials are among the most prevalent platforms for detecting metals in water due to their high electrical conductivity, high surface area, and adsorption capacity for metal ions. As an example, Ruecha N et al. (Ruecha et al., 2015) synthesized a nanocomposite electrode comprising graphene and polyaniline on a plastic substrate to detect Zn^{2+}, Cd^{2+}, and Pb^{2+} using square-wave anodic stripping voltammetry (SWASV). The sensor had detection limits of 1 µg/L of Zn^{2+} and 0.1 µg/L of Cd^{2+} and Pb^{2+} with a linear detection range of 1-300 µg/L in environmental samples. The sensitivity of the graphene-polyaniline composite is high because the conductive graphene framework and the electroactive polymer matrix interact synergistically, thereby increasing the electron-transfer rate and the effective electroactive surface area of the electrode. The sensitivity of the analysis is even higher in hybrid nanocomposite systems that combine carbon nanostructures and functional nanomaterials. Baghayeri et al. (Baghayeri et al., 2019) described a dendrimer-functionalized magnetic graphene oxide nanocomposite (GO-Fe_3O_4-PAMAM)-modified glassy carbon electrode for the simultaneous determination of Pb^{2+} and Cd^{2+} using SWASV. The sensor had a detection limit of 130 ng/L of Pb^{2+} and Cd^{2+} with spacious linear ranges of 0.4–120 µg/L and 0.2–140 µg/L,

respectively. The inclusion of magnetic Fe_3O_4 nanoparticles and PAMAM dendrimers significantly enhanced the adsorption of heavy metal ions and charge transfer in electrochemical measurements, owing to their distinctive two-dimensional structure and high electron mobility. Graphdiyne-based nanomaterials are promising candidates for improved sensing platforms to detect heavy metals, owing to their distinctive two-dimensional structure and high electron mobility. Y. Ai et al. (Ai et al., 2023) have developed a Bi/GDY (bismuth/graphdiyne) nanocomposite-based glassy carbon electrode, as shown in Fig. 5a and c, that can simultaneously detect Zn^{2+}, Cd^{2+}, and Pb^{2+} via DPASV. In a linear regime between 10 nM and 100 µM, the sensor achieved ultra-low detection limits of 0.115 nM for Zn^{2+}, 0.171 nM for Cd^{2+}, and 0.146 nM for Pb^{2+} in seawater samples. Similarly, Li et al. [58] reported a graphdiyne-based electrode that detected Cd^{2+} and Pb^{2+} in water samples by anodic stripping voltammetry, with detection limits of 0.46 nM and 1.72 nM, respectively. These works emphasize the superior electron-transporting properties and adsorption capabilities of graphdiyne materials, which contribute significantly to electrochemical sensing.

Nanomaterials of noble metals have also been extensively used to enhance the sensitivity of electrochemical sensors for detecting heavy metals in aqueous media—for example, Jia et al. (Jia et al., 2025) designed a SWASV-based gold electrode with a gold nanocluster on its surface to detect both Pb^{2+} and Cd^{2+}. The sensor showed a very low detection limit of 1 ng/L and a linear detection range of 1-250 µg/L in environmental water samples. The outstanding analytical capability of this sensor stems from the catalytic activity and high electrical conductivity of gold nanostructures, which enable rapid electron transfer and increase the concentration of metal ions at the electrode surface. On the same note, Bernalte et al. (Bernalte et al., 2012a) developed a gold nanoparticle-modified screen-printed carbon electrode to detect and quantify Hg^{2+} in environmental water samples, such as rivers, rainwater and wastewater, with a detection limit of 0.8 µg/L using SWASV. Stripping voltammetric methods, i.e., square-wave anodic stripping voltammetry (SWASV) and differential pulse anodic stripping voltammetry (DPASV), are the most popular among electrochemical techniques due to their built-in preconcentration capability. This is done to enable the metal ions to settle on the electrode surface before stripping, thereby increasing the analysis's sensitivity.

Metal oxide nanomaterials have also been utilized in electrochemical sensors. Moussaoui et al. (Moussaoui et al., 2023) constructed a NiO nanoparticle-functionalized graphite carbon electrode and used SWASV to detect Cu^{2+} in drinking water, achieving a detection limit of 3.83×10^{-9} M (see Fig. 5b and d). Moreover, composite systems comprising carbon nanomaterials and metallic nanoparticles have exhibited more effective detection capabilities due to the synergistic effects of their nanostructured architecture. A study by Wang et al. (W.-J. Wang et al., 2022) reported an electrode composed of reduced graphene oxide and supported by Au-Bi bimetallic nanoparticles for the concomitant detection of Pb^{2+} and Cd^{2+} using DPASV, with detection limits of 0.05 µM and 0.02 µM, respectively, in river water samples.

Sensing platforms on carbon nanotubes have also been extensively explored for monitoring heavy metals in drinking water. To illustrate, Alam et al. (Alam et al., 2019) prepared a β-cyclodextrin-multi-walled carbon nanotube (MWCNT) composite screen-printed electrode (SP) that was used to detect Pb^{2+} ions by DPASV, with a detection limit of 0.9 ppb in drinking water samples. Carbon nanotubes have a high surface area and high electrical conductivity, which enable efficient electrochemical adsorption of metal ions and rapid electron transfer, thereby improving electrochemical sensitivity. Although most nanosensor platforms have a high surface area, their detection limits are usually relatively high for the electrode modification strategy. For example, the polyglycine-functionalized graphene electrode described by Raril and Manjunatha (Raril & Manjunatha, 2020) for simultaneous detection of Hg^{2+} and Pb^{2+} had detection limits in the micromolar range, which are lower than those of hybrid nanocomposite-based sensors. This change emphasizes the importance of selecting nanomaterials and designing electrodes to influence sensor functionality.

Table 2
Literature review of electrochemical nanosensors for heavy metal detection in water.

Nanomaterial	Electrode	Electrochemical Technique	Target Metal	LOD	Linear Range	Initial/Test Concentration	Response Time	Sample Matrix	Reference
Graphene–polyaniline nanocomposite	Plastic substrate electrode	SWASV	Zn^{2+}, Cd^{2+}, Pb^{2+}	Zn: 1 µg/L, Cd: 0.1 µg/L, Pb: 0.1 µg/L	1–300 µg/L	Standard addition method	Not specified	Environmental samples	(Ruecha et al., 2015)
GO-Fe_3O_4-PAMAM	Glassy carbon electrode	SWASV	Pb^{2+}, Cd^{2+}	Pb: 130 ng/L, Cd: 70 ng/L	Pb: 0.4–120 µg/L, Cd: 0.2–140 µg/L	−1.1 V accumulation	160 s	Water samples	(Baghayeri et al., 2019)
Bi/GDY nanocomposite	Glassy carbon electrode	DPASV	Zn^{2+}, Cd^{2+}, Pb^{2+}	Zn: 0.115 nM, Cd: 0.171 nM, Pb: 0.146 nM	10 nM – 100 µM	−1.3 V deposition	150 s	Seawater	(Ai et al., 2023)
Gold nanoclusters	Gold electrode	SWASV	Pb^{2+}, Cd^{2+}	1 ng/L	1–250 µg/L	−0.4 V enrichment	390 s	Environmental water	(Jia et al., 2025)
AuNP modified SPCE	Screen-printed carbon electrode	SWASV	Hg^{2+}	0.8 µg/L (0.8 ppb)	Not specified	+ 0.2 V deposition	120 s	River water/wastewater	(Bernalte et al., 2012a)
NiO nanoparticles	Carbon graphite electrode	SWASV	Cu^{2+}	3.83×10^{-9} M	$0–1.5 \times 10^{-7}$ M	Not specified	Not specified	Drinking water	(Moussaoui et al., 2023)
rGO/Au-Bi bimetallic nanoparticles	Glassy carbon electrode	DPASV	Pb^{2+}, Cd^{2+}	Pb: 0.05 µM, Cd: 0.02 µM	Pb: 0.1–500 µg/L, Cd: 0.1–300 µg/L	−1.0 V deposition	200 s	River water	(W.-J. Wang et al., 2022)
MWCNT-βCD composite	Screen-printed electrode	DPASV	Pb^{2+}	0.9 ppb	Not clearly specified	−0.8 V deposition	600 s	Drinking water	(Alam et al., 2019)
Polyglycine modified graphene	Graphene paste electrode	CV / DPV	Hg^{2+}, Pb^{2+}	Hg: 6.6 µM, Pb: 0.8 µM	Not specified	Not specified	Not specified	Water and serum	(Raril & Manjunatha, 2020)
Graphdiyne	Glassy carbon electrode	ASV	Cd^{2+}, Pb^{2+}	Cd: 0.46 nM, Pb: 1.72 nM	0.01–1 µM	−1.2 V enrichment	600 s	Water	(Y. Li et al., 2021)

4.2 Review of nanosensors for heavy metals in milk and dairy products

Milk and dairy products are complex food matrices for heavy metal detection because they contain proteins, lipids, lactose, and other mineral components that may interfere with electrochemical measurements. Such constituents can influence the adsorption of metal ions at electrode surfaces, leading to electrode fouling during voltammetric analysis. This has necessitated the development of nanomaterial-based electrochemical sensors with improved surface characteristics, high conductivity, and increased adsorption capacity, capable of detecting trace levels of heavy metals in dairy matrices with high precision. Table 3 summarizes various electrochemical nanosensor platforms developed for testing milk and dairy products. Bismuth nanomaterials on carbon have also been widely used for the electrochemical detection of heavy metals in milk samples due to their high conductivity and environmental friendliness compared with mercury-based electrodes. Ping et al. (Ping et al., 2014) used a bismuth film combined with a screen-printed electrode containing electrochemically reduced graphene oxide to fabricate a bismuth-film screen-printed electrode, which was used to concurrently detect Cd^{2+} and Pb^{2+} in milk by square-wave anodic stripping voltammetry (SWASV). The sensor had a detection limit of 0.5 µg/L of Cd^{2+} and 0.8 µg/L of Pb^{2+} in a linear range of detection of 160 µg/L, which illustrated the benefits of graphene-based nanostructures in improving the rate of electrotransfer and enhancing electroactive surface area. These same enhancements were observed with sensors built on single-walled carbon nanohorns with bismuth films, wherein Yao et al. (Yao et al., 2019) reported detection limits of 0.2 µg/L for Cd^{2+} and 0.4 µg/L for Pb^{2+} in milk samples using SWASV.

Along with graphene-based materials, nanoporous carbon electrodes have also shown strong potential for detecting heavy metals in dairy matrices. They are highly sensitive due to their large surface area and strong adsorption capacity for heavy metal ions. In a study conducted by Chen et al. (H. Chen et al., 2023), a nanoporous carbon-modified screen-printed electrode was fabricated, and square-wave stripping voltammetry was used to detect Pb^{2+} and Cd^{2+} in infant milk powder. It had detection limits of 0.1 µg/L Pb^{2+} and 1.67 µg/L Cd^{2+} with a linear range of 1–60 µg/L and 5–70 µg/L, respectively (Fig. 6e-g). The carbon structure is highly porous, providing abundant active adsorption sites for metal ions and enabling rapid electron transfer during electrochemical measurements, thereby enhancing analytical sensitivity.

There are also numerous studies on hybrid nanocomposite systems to enhance sensor activity within complex dairy matrices. Zhang and Guo et al. (M. Zhang & Guo, 2023) described a magnetic glassy carbon electrode that was coated with $Fe_3O_4@SiO_2$ core-shell nanoparticles to detect Cd^{2+}, Pb^{2+}, Cu^{2+}, and Hg^{2+} in milk samples by performing differential pulse stripping voltammetry. The magnetic nanostructures also offer improved adsorption and separation of metal ions in the sample matrix, enabling detection of heavy metals at nanomolar concentrations. Other benefits of such magnetic nanomaterial platforms are sample enrichment and enhanced sensitivity in complex systems such as food systems.

Conductive polymer-carbon nanocomposite electrodes have also demonstrated excellent performance towards heavy metal detection in dairy products. Wang et al. (F. Wang et al., 2025) tested an N-doped reduced graphene oxide with a polypyrrole-modified electrode in the simultaneous detection of Pb^{2+} and Cd^{2+} using SWASV, seen in Fig. 6a and b. The sensor had good detection limits of 0.080 µg/L for Pb^{2+} and 0.029 µg/L for Cd^{2+} in milk samples, with a wide linear detection range of 1-500 µg/L (Fig. 6c and d). This synergistic interaction between nitrogen-doped graphene and conductive polymer matrices enables more efficient electron transfer and greater conductivity, provides more active adsorption sites, and results in higher detection sensitivity. Shahbazi et al. (Shahbazi et al., 2016) employed a hanging mercury drop electrode (HMDE) and differential pulse stripping voltammetry to simultaneously detect Pb^{2+}, Cd^{2+}, Zn^{2+}, Cu^{2+}, and Se in milk, cheese, and yogurt samples. Although mercury electrodes have high analytical sensitivity, their practical application is increasingly limited due to the toxicity of mercury-based sensing platforms. Even though nanomaterial-modified electrodes offer significant analytical benefits, there are still sensing systems where detection limits remain relatively high due to the electrode modification approach. For example, electrodes modified with bismuth nanoparticles coated with Nafion showed relatively high detection limits of 7.31 µg/L for Cd^{2+} and 31.07 µg/L for Pb^{2+} in ultra-high-temperature (UHT) milk samples (S. Palisoc et al., 2019). Such variation can be explained by differences in electrode design and the complex structures of processed dairy products, which can affect analyte adsorption and electrochemical signals.

Table 3
Literature review of electrochemical nanosensors for heavy metal detection in milk and dairy products.

Nanomaterial	Electrode	Electrochemical Technique	Target Metal	LOD	Linear Range	Initial/Test Concentration	Response Time	Sample Matrix	Reference
Electrochemically reduced graphene oxide + Bi film	Screen-printed electrode	SWASV	Cd^{2+}, Pb^{2+}	Cd: 0.5 µg/L, Pb: 0.8 µg/L	1–60 µg/L	−1.2 V deposition	150 s	Milk	(Ping et al., 2014)
Single-walled carbon nanohorns + Bi film	Screen-printed electrode	SWASV	Cd^{2+}, Pb^{2+}	Cd: 0.2 µg/L, Pb: 0.4 µg/L	1–60 µg/L	−1.2 V deposition	150 s	Milk	(Yao et al., 2019)
Nanoporous carbon	Screen-printed electrode	Square-wave stripping voltammetry	Cd^{2+}, Pb^{2+}	Pb: 0.1 µg/L, Cd: 1.67 µg/L	Pb: 1–60 µg/L; Cd: 5–70 µg/L	−1.0 V deposition	160 s	Infant milk powder	(H. Chen et al., 2023)
$Fe_3O_4@SiO_2$ magnetic nanoparticles	Magnetic glassy carbon electrode	Differential pulse stripping voltammetry	Cd^{2+}, Pb^{2+}, Cu^{2+}, Hg^{2+}	Nanomolar range	Cd: 0.1–100 µM; Pb: 0.01–100 µM	−1.2 V deposition	150 s	Milk	(M. Zhang & Guo, 2023)
N-doped reduced graphene oxide + polypyrrole	Glassy carbon electrode / SPE	SWASV	Pb^{2+}, Cd^{2+}	Pb: 0.080 µg/L, Cd: 0.029 µg/L	1–500 µg/L	−1.2 V deposition	600 s	Milk	(F. Wang et al., 2025)
Bismuth nanoparticles + Nafion	Pencil graphite electrode	ASV	Cd^{2+}, Pb^{2+}	Cd: 7.31 µg/L, Pb: 31.07 µg/L	10–150 µg/L	−0.8 V deposition	80 s	UHT milk	(S. Palisoc et al., 2019)
Conventional electrode (HMDE)	Hanging mercury drop electrode	Differential pulse stripping voltammetry	Pb^{2+}, Cd^{2+}, Zn^{2+}, Cu^{2+}, Se^{2+}	Pb:0.25 ppb, Cd: 0.12 ppb, Zn: 0.05 ppb, Cu: 0.04 ppb, Se: 0.14 ppb	Pb: 0.5–200 ppb, Cd: 0.3–220 ppb, Zn: 0.1–500, Cu: 0.1–450, Se: 0.4–120	−1.15 V accumulation	Not specified	Raw Milk	(Shahbazi et al., 2016)

4.3 Review of nanosensors for heavy metals in seafood and fish

Fish products and seafood are relevant components of the human diet and are known to harbor heavy metals from aquatic ecosystems, which are acquired through bioaccumulation and biomagnification. Marine organisms can take up toxic metallic particles of mercury (Hg^{2+}), lead (Pb^{2+}), cadmium (Cd^{2+}), and copper (Cu^{2+}) from contaminated water, sediments, and food chains, which are subsequently transferred into human food systems through seafood consumption. Considering the complex biochemical composition of fish tissues, including proteins, lipids, and bioactive compounds, both sensitive analytical methods and effective electrode modification approaches are essential for detecting trace heavy metals in seafood matrices. Nanomaterial-based electrochemical sensors have emerged as alternatives for such applications due to their high sensitivity, rapid response, and on-site monitoring capabilities. Table 4 lists various electrochemical nanosensors developed to detect heavy metals in seafood and fish matrices.

MOF nanomaterials have proven to be excellent sensing platforms because they are highly porous, can form numerous structures, and have high adsorption capacities for metal ions. As an illustration, Vlachou E et al. (Vlachou et al., 2020) designed a calcium metal-organic framework (Ca-MOF) functionalized carbon paste electrode to detect Pb^{2+} in fish feed using anodic stripping voltammetry (ASV). The sensor had a detection limit of 0.26 µg/L after preconcentration (360 s at 1.2 V). Singh et al. (Singh et al., 2020) synthesized a copper metal-organic framework (Cu-MOF)-functionalized glassy carbon electrode (Fig. 7 (d)) to detect Hg^{2+} in tuna fish that has been canned using the methods of differential pulse voltammetry and cyclic voltammetry. The sensor had a very low detection of 0.0633 nM and a linear range of 0.1–50 nM in phosphate buffer solution. MOF structures exhibit high porosity and strong adsorption capacity, facilitating the efficient deposition of mercury ions on the electrode surface and thereby intensifying electrochemical signals, as shown in Fig. 7 (e-h).

Sensing platforms based on noble metal nanoparticles have also demonstrated high analytical sensitivity for mercury in fish samples. Mercury is highly attracted to the surface of gold, and therefore, gold-based electrodes are most efficient in Hg^{2+} detection. Ruo Redda et al. (Ruo Redda et al., 2019) used gold nanoparticles on a gold electrode surface to determine mercury in tuna fish samples using square-wave anodic stripping voltammetry, with a detection limit of 0.1 µg/L. Likewise, Radulescu and Danet et al. (Radulescu & Danet, 2008) reported that a gold working electrode was used to detect mercury in fish samples by chronopotentiometric stripping analysis, with a detection limit of 0.30 µg/L after deposition at 0.3 V for 600 s. Elsewhere, Vasquez-Velarde et al. (Vásquez-Velarde et al., 2023) applied AuNP-modified carbon-fiber microelectrodes with differential pulse anodic stripping voltammetry to detect mercury in canned tuna samples, with a detection limit of 3.98 µg/L. These experiments demonstrate that mercury ions and gold surfaces exhibit a strong electrochemical affinity, thereby enhancing preconcentration and signal formation during electrochemical analysis.

Hybrid nanocomposite materials composed of porous polymers and metal nanoparticles have also been reported to exhibit high analytical capabilities for detecting multiple heavy metals in seafood matrices. Huang et al. (Huang et al., 2024) prepared a conjugated mesoporous polymer with bismuth nanoparticles (CMP-BiNP)-modified screen-printed carbon electrode to detect Pb^{2+} and Cd^{2+} by simultaneous square-wave anodic stripping voltammetry (Fig. 7 (a)-(c)). When used on samples of fish, shrimp, and squid, the sensor had a detection limit of 0.1 µg/L with Pb^{2+} and 0.2 µg/L with Cd^{2+} and a linear detection range of 1-100 µg/L. This synergistic effect between the porous polymer matrix and bismuth nanoparticles enhances metal-ion adsorption and rapid electron transfer, resulting in high electrochemical sensitivity. Unmodified electrode-based sensors tend to exhibit much lower analytical sensitivity. Indicatively, Onac and Kaya et al. (Onac & Kaya, 2025) used an unmodified screen-printed electrode to detect Cu^{2+} in fish liver samples by cyclic voltammetry with a detection limit of 0.080 mM and a linear detection range of 0.25-10 mM. The relatively low sensitivity of the study indicates that modifying the electrode with nanostructured materials is necessary to increase adsorption capacity and electron-transfer rate.

Multi-metal detection in seafood samples has also been done using classical electrochemical sensing platforms. In the study by Meucci et al. (MEUCCI et al., 2009) Mercury-modified graphite screen-printed electrodes were used with square-wave anodic stripping voltammetry to detect Pb^{2+}, Cd^{2+}, Cu^{2+}, and Hg^{2+} in fish muscle samples. Although these systems offer extensive multi-element detection, the mercury-based electrodes used pose environmental and safety risks that limit their large-scale use. Fisheries matrices are even more analytically challenging due to the bioaccumulation of heavy metals in fish tissues and the high levels of proteins and lipids. These aspects may require sample pretreatment, such as acid digestion, to dissociate bound metal ions before electrochemical analysis.

Table 4
Literature review of electrochemical nanosensors for heavy metal detection in seafood and fish.

Nanomaterial / Modifier	Electrode	Electrochemical Technique	Target Metal	LOD	Linear Range	Deposition / Initial Conditions	Response Time	Sample Matrix	Reference
Calcium metal–organic framework (Ca-MOF)	Carbon paste electrode	Anodic stripping voltammetry (ASV)	Pb	0.26 µg/L	Not specified	−1.2 V preconcentration	360 s	Fish feed	(Vlachou et al., 2020)
Gold nanoparticles	Gold electrode / AuNP modified GCE	Square wave anodic stripping voltammetry	Hg	0.1 µg/L	Not specified	Acid digestion prior to detection	Not specified	Tuna fish	(Ruo Redda et al., 2019)
Gold electrode	Gold working electrode	Chronopotentiometric stripping analysis	Hg	0.30 µg/L	Not specified	0.3 V deposition	600 s	Fish samples	(Radulescu & Danet, 2008)
AuNP	Carbon fiber microelectrode	Differential pulse anodic stripping voltammetry	Hg	3.98 µg/L	Not specified	Acid digestion	Not specified	Canned tuna	(Vásquez-Velarde et al., 2023)
Conjugated mesoporous polymer + BiNP	Screen-printed carbon electrode	Square wave anodic stripping voltammetry	Pb, Cd	Pb: 0.1 µg/L Cd: 0.2 µg/L	1–100 µg/L	−1.4 V deposition for 300 s	300 s	Fish, shrimp, squid	(Huang et al., 2024)
None (unmodified electrode)	Screen-printed electrode	Cyclic voltammetry	Cu	0.080 mM	0.25–10 mM	Drop-cast sample	Not specified	Fish liver	(Onac & Kaya, 2025)
Hg-modified graphite SPE	Screen-printed electrode	Square wave anodic stripping voltammetry	Pb, Cd, Cu, Hg	Not specified	1 µg/L – 1 mg/L	−1.1 V deposition	120 s	Fish muscle	(MEUCCI et al., 2009)
Copper metal-organic framework (Cu-MOF)	Cu-MOF modified glassy carbon electrode	Differential pulse voltammetry / cyclic voltammetry	Hg	0.0633 nM	0.1–50 nM	0.1 M PBS (pH 9)	Not specified	Canned tuna fish	(Singh et al., 2020)

4.4 Review of nanosensors for heavy metals in fruits and vegetables

Fruits and vegetables are part of the human diet and are widely consumed because they are the main sources of vitamins, minerals, and fiber. Pollution of food crops with harmful heavy metals has been an increasing environmental and health issue. Heavy metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), mercury (Hg^{2+}), and copper (Cu^{2+}) may enter plant tissues through contaminated soil, irrigation water, fertilizers, pesticides, and atmospheric deposition. These metals can accumulate in plant edible parts and thus enter the human food chain. Because of the complex chemical structure of plant-based food matrices, which include organic acids, carbohydrates, pigments, and other plant metabolites, precise quantification of heavy metals requires highly sensitive and selective analytical methods. Nanomaterial-based electrochemical sensors have demonstrated significant potential for detecting heavy metal contamination in fruits and vegetables in recent years, given their high sensitivity, rapid response, and compatibility with portable analytical devices. Table 5 summarizes key electrochemical nanosensors that have been developed to detect heavy metals in fruit and vegetable matrices.

Bismuth film-based electrodes have been widely used for the electrochemical detection of heavy metals in plant-derived food samples, providing an environmentally friendly alternative to mercury electrodes while maintaining high sensitivity in sample analysis. According to Tesfaw et al. (Tesfaw et al., 2018) a Nafion-coated bismuth film-modified glassy carbon electrode was used to detect Pb^{2+} in vegetables, including tomato, cabbage, and onion, using square-wave anodic stripping voltammetry (SWASV). The sensor was found to have a detection limit of about 10^{-10} M after a 240 s deposition step at 1.2 V. The Nafion coating enhances selectivity by allowing cation exchange at least with other ionic species in plant extracts.

Nanomaterials based on clay have also been used in sensing platforms. Knihnicki et al. (Knihnicki et al., 2022) developed a halloysite nanotube- and multiwalled carbon nanotube-modified electrode for the detection of Pb^{2+} and Cd^{2+} by differential pulse anodic stripping voltammetry (DPASV). The presence of nanotubular clay minerals and carbon nanotubes increases the electrode surface area and the electrochemical response to heavy metal ions. The sensor showed good linearity over 0.1–10 µmol/L (LOD of 0.0051 µmol/L for Pb^{2+} and 0.0106 µmol/L for Cd^{2+}) for water and honey samples.

Multi-metal detection in agricultural samples has also been found to be good using hybrid nanocomposite platforms based on carbon nanomaterials and metal oxide nanoparticles. Wu et al. (Wu et al., 2019) developed a sensor based on Fe_3O_4 nanoparticles and fluorinated multi-walled carbon nanotubes (MWCNTs) deposited on a glassy carbon electrode, which can simultaneously detect Pb^{2+}, Cd^{2+}, Cu^{2+}, and Hg^{2+} using SWASV, as shown in Fig. 9 (a-c). The sensor demonstrated very low detection limits of 0.02–0.08 nM in soybean food samples at a deposition step of 1.2 V over 180 s. Conductive carbon nanotubes, in conjunction with magnetic nanoparticles, enhance electron transfer efficiency and provide numerous active adsorption sites for heavy metal ions, thereby increasing electrochemical sensitivity.

Green synthesis methods have also been considered for developing environmentally friendly electrochemical sensors to monitor agriculture. Incebay et al. (Incebay et al., 2020) presented a green tea extract-functionalized MWCNT composite electrode for detecting Cd^{2+} using differential pulse anodic stripping

voltammetry (DPASV). The sensor was found to have a detection limit of 1.01 nM and a linear range of 0.05-6 μM after a deposition at 1.5 V for 120 s. Plant functional groups in the green tea extract facilitate the strong adsorption of metal ions onto the electrode surface and enhance the stability of the nanocomposite structure.

Electrochemical sensors, particularly nanochannel-based sensors, have also become promising detectors of heavy metals in fruit-based beverages. Li G et al. (G. Li et al., 2021) created a PDMS@MSF nanochannel film stacked onto an indium tin oxide (ITO) electrode to detect Pb^{2+} and Cd^{2+} concurrently by a differential pulse anodic stripping electrochemical method. The nanochannel is selectively permeable to ions, anti-fouling, and allows detection in complex samples such as fruit juice and beverages, as shown in Fig. 8. The sensor showed wide linear detection limits of 4-1500 μg/L for Pb^{2+} and 30–900 μg/L for Cd^{2+}.

Hybrid carbon nanocomposites have also excelled at analyzing heavy metals in plant-based foods. Karazan Z et al. (Karazan & Roushani, 2023) designed a poly(riboflavin)-carbon black composite-modified glassy carbon electrode for the simultaneous measurement of Pb^{2+} and Cd^{2+} by DPASV. When used with food samples, including rice, honey, lettuce, and tomato, the sensor achieved ultra-low detection limits of 0.13 nM and 0.16 nM for Pb^{2+} and Cd^{2+}, respectively, with a linear detection range of 0.5–600 nM. The conductive carbon matrix provides a rapid pathway for electron transfer, and the polymer film enhances the adsorption of metal ions. The analysis of vegetables using metal-oxide hybrid nanomaterials has also proven promising. Yang et al. (Y. Yang et al., 2025) prepared a SnO_2-g-C_3N_4-MWCNT composite-modified glassy carbon electrode and used it to simultaneously detect Pb^{2+} and Cd^{2+} in leafy vegetables such as spinach, lettuce, and cabbage by differential pulse stripping voltammetry. The sensor could detect 0.40 μg/L Pb^{2+} and 0.61 μg/L Cd^{2+} after enrichment for 330 s at -1.1 V. The combination of metal oxide nanostructures with carbon nanotubes is synergistic, thereby enhancing electrode conductivity and saturation sites for active adsorption.

Nanocomposites containing silver nanoparticles have also been used to detect heavy metals in agricultural products. Palisoc et al. (S. T. Palisoc et al., 2018) described the detection of Pb^{2+} and Cd^{2+} in organic and nonorganic vegetable samples by anodic stripping voltammetry with a silver nanoparticle-MWCNT-Nafion composite-modified glassy carbon electrode. The sensor showed a detection limit of 0.216 ppb to Pb^{2+} and 0.481 ppb to Cd^{2+} with a linear detection limit of 0.493-157 ppb and 1.864-155 ppb, respectively. Silver nanoparticles are incorporated to increase catalytic activity, while the Nafion layer increases ion selectivity.

Another innovation is the application of molecular recognition features, such as aptamers, to enhance detection specificity. Yuan et al. (Yuan et al., 2022) designed an aptamer-functionalized gold electrode to selectively detect Pb^{2+} and Cd^{2+} with square-wave voltammetry (Fig. 9d). The sensor demonstrated detection limits of 16.44 pmol/L for Pb^{2+} and 89.31 pmol/L for Cd^{2+}, and a wide linear detection range (0.1–1000 nmol/L) when tested on samples of fruits and vegetables, including oranges and lettuce. The aptamer molecules have high, specific binding affinity for certain metal ions, thereby enhancing the selectivity of analysis in complex plant-based matrices.

Table 5
Literature review of electrochemical nanosensors for heavy metal detection in fruits and vegetables.

Nanomaterial / Modifier	Electrode	Electrochemical Technique	Target Metal	LOD	Linear Range	Deposition / Initial Conditions	Response Time	Sample Matrix	Reference
Nafion-coated bismuth film	Glassy carbon electrode	SWASV	Pb^{2+}	~ 10^{-10} M	Not specified	−1.2 V deposition, 240 s	Not specified	Tomato, cabbage, onion	(Tesfaw et al., 2018)
Halloysite nanotubes + MWCNT	Screen-printed carbon electrode	DPASV	Pb^{2+}, Cd^{2+}	Pb: 0.0051 µmol/L, Cd: 0.0106 µmol/L	0.1–10 µmol/L	−1.0 V deposition	Not specified	HONEY AND WATER	(Knihnicki et al., 2022)
Fe_3O_4 nanoparticles + fluorinated MWCNT	Glassy carbon electrode	SWASV	Pb^{2+}, Cd^{2+}, Cu^{2+}, Hg^{2+}	0.02–0.08 nM	0.5–30 µM	−1.2 V deposition, 180 s	~ 180 s	Soybean food sample	(Wu et al., 2019)
Green tea extract + MWCNT composite	Glassy carbon electrode	DPASV	Cd^{2+}	1.01 nM	0.05–6 µM	−1.5 V deposition, 120 s	~ 120 s	Agricultural water (crop contamination)	(Incebay et al., 2020)
PDMS@MSF nanochannel film	ITO electrode	DPASV	Pb^{2+}, Cd^{2+}	Not specified	Pb: 4–1500 µg/L; Cd: 30–900 µg/L	Electro-deposition stripping	Not specified	Fruit juice and beverages	(G. Li et al., 2021)
PRF + carbon black composite	Glassy carbon electrode	DPASV	Pb^{2+}, Cd^{2+}	Pb: 0.13 nM; Cd: 0.16 nM	0.5–600 nM	In-situ Bi^{3+} deposition	Not specified	Rice, honey, lettuce, tomato	(Karazan & Roushani, 2023)
SnO_2 + g-C_3N_4 + MWCNT	Glassy carbon electrode	DPSV	Pb^{2+}, Cd^{2+}	Pb: 0.40 µg/L; Cd: 0.61 µg/L	10–400 µg/L	−1.1 V enrichment, 330 s	~ 330 s	Spinach, lettuce, cabbage	(Y. Yang et al., 2025)
Silver nanoparticles + MWCNT + Nafion	Glassy carbon electrode	ASV	Pb^{2+}, Cd^{2+}	Pb: 0.216 ppb; Cd: 0.481 ppb	Pb: 0.493–157 ppb; Cd: 1.864–155 ppb	−0.9 V deposition, 60 s	~ 60–90 s	Organic and non-organic vegetables	(S. T. Palisoc et al., 2018)
Aptamer-modified Au electrode	Gold electrode	SWV	Pb^{2+}, Cd^{2+}	Pb: 16.44 pmol/L; Cd: 89.31 pmol/L	0.1–1000 nmol/L	Incubation with the analyte	~ 30 min	Orange, lettuce	(Yuan et al., 2022)

5. Critical Discussion

5.1 Summary of Nanomaterials Used In Electrochemical Sensing

The introduction of nanomaterials has radically changed the design of electrochemical sensors to detect heavy metals. Nanostructured materials offer a range of advantages, including a larger electroactive surface area, improved electron transfer kinetics, and greater adsorption capacity for metal ions. These properties enable efficient preconcentration of analytes and sensitive electrochemical detection. It was previously discussed that surface modifications of electrodes with carbon nanomaterials, metal nanoparticles, and metal oxides may significantly enhance the electrochemical response signals and reduce the limits of detection in relation to bare electrodes (Fakayode et al., 2023; Naresh & Lee, 2021; Waheed et al., 2018). Carbon-based materials, including graphene, reduced graphene oxide, and carbon nanotubes, are the most widely used among the various nanomaterials reported in the literature, owing to their high conductivity and large surface area (Saqib et al., 2025). These materials are effective electron mediators that facilitate rapid charge transfer during electrochemical reactions. As an example, graphene-polyaniline nanocomposite electrodes have been shown to detect Zn^{2+}, Cd^{2+}, and Pb^{2+} in environmental water samples with a 0.1 µg/L detection limit (Ruecha et al., 2015). Likewise, electrodes made of graphdiyne were also reported to allow the sensitive detection of Cd^{2+} and Pb^{2+} at nanomolar concentrations owing to their two-dimensional geometry and high electron mobility (Y. Li et al., 2021). The use of metal nanoparticles is also significant in enhancing the performance of electrochemical sensors. Noble metal nanostructures, such as AuNPs, are effective catalysts with high electrical conductivity, which are important for amplifying electrochemical signals. As an example, gold nanoparticles (AuNPs) have been extensively used as electrode modifications to make sensitive mercury detection in environmental and food samples because mercury ions attach strongly to the gold surfaces (Bernalte et al., 2012b; Gong et al., 2010b). Moreover, hybrid nanocomposite materials based on carbon nanomaterials with metal nanoparticles have shown synergy that complements the sensor functions by enhancing the density of active binding sites and electron transfer reactions (Meng et al., 2023b).

5.2 Influence of Food Matrix Complexity on Electrochemical Detection

The analytical performance of electrochemical nanosensors is strongly dependent on the complexity of the food matrix being studied. Water samples are usually the simplest analytical environment because the concentration of interfering compounds is relatively low. Consequently, sensors used in aqueous matrices tend to exhibit the lowest detection limits and stable electrochemical reactions. For example, graphdiyne-modified electrodes and sensors based on gold nanoclusters have demonstrated extremely low detection limits for heavy metal ions in environmental water samples (Jia et al., 2025; Y. Li et al., 2021). Conversely, dairy products pose more challenging analytical conditions due to their complex biochemical composition. Milk contains proteins, fats, lactose, and other inorganic salts, which can interact with electrode surfaces and disrupt electrochemical measurements. Therefore, appropriate methods of electrode modification and sample pretreatments are required to reduce the effects of the matrix. It has been demonstrated that electrodes made of graphene with bismuth films can also measure trace Pb^{2+} and Cd^{2+} in milk samples, indicating that carbon nanostructures can be successfully used to enhance electrochemical sensitivity in complex food samples (Ping et al., 2014; Yao et al., 2019). The analysis of seafood and fish presents further analytical challenges due to the bioaccumulation of heavy metals in fish tissues. Proteins and lipids are often present in large amounts in marine organisms, making detection by electrochemical methods challenging. Nonetheless, nanostructured electrode materials, such as metal-organic frameworks (MOFs), have demonstrated good performance for mercury detection in seafood samples. For example, electrodes based on Cu-MOF have enabled the detection of Hg^{2+} in canned tuna samples with a detection limit in the nanomolar range (Singh et al., 2020). Correspondingly, conjugated mesoporous polymer-bismuth nanoparticle composites have been utilized successfully in the detection of Pb^{2+} and Cd^{2+} in seafood samples concurrently by square-wave anodic stripping voltammetry (Huang et al., 2024). Fruits and vegetables are plant-derived foods and contain a variety of organic compounds, including pigments, organic acids, and plant metabolites, that can interfere with electrochemical measurements. However, hybrid nanocomposite sensors have performed very well in detecting heavy metals in such matrices. For example, in a study on soybean food, Fe_3O_4-MWCNT composite electrodes have demonstrated exceptionally low detection limits for multiple heavy metal ions (Wu et al., 2019), and PRF-carbon black composite electrodes have demonstrated the ability to detect both Pb^{2+} and Cd^{2+} in vegetables and grains with nanomolar sensitivity (Karazan & Roushani, 2023).

5.3 Comparative Analysis of Detection Limits

Among the most important aims of this review was to assess the analytical performance of electrochemical nanosensors by comparing reported limit-of-detection studies. It is found that the majority of nanomaterial-based electrochemical sensors can detect in the nanomolar or subnanomolar range, indicating they can detect heavy metals at trace levels. In a few studies, detection down to picomolar levels has also been achieved, especially when molecular recognition components, such as aptamers, are incorporated into sensor design. Indicatively, aptamer-modified gold electrodes have shown a remarkably high selectivity and sensitivity in the detection of Pb^{2+} in fruit and vegetable samples, with detection limits of 16.44 pmol/L (Yuan et al., 2022). Equally, with a detection limit of 0.02 nM for several heavy metal ions, Fe_3O_4-MWCNT nanocomposite sensors demonstrate the strong capability of hybrid nanostructured materials to enable electrochemical sensing (Wu et al., 2019). These results affirm that the addition of nanomaterials to electrochemical sensing systems significantly enhances the sensitivity of analysis compared to traditional electrodes. Stripping voltammetric methods, such as square-wave anodic stripping voltammetry (SWASV) and differential pulse anodic stripping voltammetry (DPASV), are among the most widely used electrochemical methods for heavy metal analysis because they can preconcentrate analytes on the electrode surface before measurement. This preconcentration step enables the detection of trace metal concentrations that would otherwise be challenging with traditional voltammetric methods (Ariño et al., 2022b; Chatziathanasiou et al., 2024).

6. Recent advancements: portable electrochemical devices for heavy metal detection in food matrices

Since selectivity (the ability to detect analytes in complex samples) poses a significant challenge in detection techniques, researchers have been developing smart sensing technologies. While conventional approaches have shown their potential for accurate, precise monitoring of food-contaminating agents, whether biological or non-biological, the rise of next-generation devices has transformed the sensing platform. These platforms offer point-of-use monitoring without requiring experts, as the devices can be connected and monitored via Bluetooth or other protocols through electronic systems such as computers, mobile phones, and tablets, thereby improving decision-making capabilities and enabling compatibility with packaging materials. Portable electrochemical devices offer rapid, sensitive, selective, and user-friendly analysis, while supporting cost-effectiveness. They achieve this by integrating miniaturized analyzers with disposable sensing platforms, such as screen-printed electrodes.

Hence, incorporating nanomaterials, including carbon-based nanostructures, metal nanoparticles, and metal–organic frameworks, plays a crucial role in enhancing sensitivity and lowering detection limits, even in compact systems. Recent advances have enabled the integration of electrochemical sensors with smartphones, wireless communication, and microfluidic platforms, facilitating real-time monitoring and data analysis. Nevertheless, ongoing developments in nanotechnology and device engineering are expected to improve performance and enable the deployment of portable electrochemical sensors for routine food safety monitoring. In a recent study, Lahari et al. (Lahari et al., 2025) reported integrating the Internet of Things (IoT) with electrochemical sensing for heavy-metal detection in water samples, as shown in Fig. 10(a). In their study, they synthesized a sensor using gold nanoparticles modified carbon thread electrodes and, subsequently, performed a DPV study. They validated their sensor performance using a convolutional neural network (CNN).

M.-M. Chen et al. (M.-M. Chen et al., 2025) developed a machine-learning-powered, fluorescence-based chemical sensor array for detecting heavy metals and pesticides, in which they used three different copper nanoclusters and coupled them with machine-learning algorithms (linear discriminant analysis: LDA and hierarchical cluster analysis: HCA), achieving 100% identification accuracy within 10 mins, with limits of detection of about 0.5 nM for heavy metal(loid)s and 7.1 ppb for pesticides. They further validated their work using complex matrices, including vegetables, fruits, tap water, soil, urine, and blood, thereby demonstrating the sensor's robustness and practical applicability for real-world monitoring. Similarly, V. Kailasam et al.(Kailasam et al., 2024) proposed a combination of experimental work with machine learning, in which they synthesized a silver oxide-bismuth oxybromide coated with Nafion as an electrochemical nanosensor, for detecting nickel and copper ions in aqueous solutions. The proposed sensor platform showed a linear response with a

correlation coefficient of 98% across varying Ni^{2+} and Cu^{2+} concentrations, while the Naïve Bayes model classifier achieved 93.2% accuracy. Hence, this study concludes that hybrid electrochemical-AI/ML systems represent an emerging direction in intelligent, automated heavy-metal monitoring.

In a different study, W. Zhang et al.(W. Zhang et al., 2020), developed a smartphone-based portable electrochemical platform for detecting heavy metals in liquid food items such as cow milk, orange juice, and apple juice, integrating a nano-Au-modified electrode and a programmable solid-state microwave flow digestion system. From this platform, they obtained a limit of detection of around 2 μgL^{-1} with high sensitivity for Cd^{2+}, $Pb^{2+,}$ and Hg^{2+}.

Further, to prioritize portability, additional next-generation sensing technology involves microfluidic integration, which provides design advantages by incorporating operational units for fluid flow regulation and sample preparation before detection, enabling enhanced, accurate, and rapid analysis within a single device (Naorungroj et al., 2026). In this regard, M. Yuan et al. (Yuan et al., 2024) reported a simple multi-channel paper-based microfluidic chip using fluorescence aptamers (Fig. 10 (b)) to detect lead (II), mercury (II), cadmium (II), and arsenic (III), obtaining a limit of detection of 4.20 nM, 1.70 nM, 2.04 nM, and 1.65 nM, respectively, which they further validated on real samples of apple and lettuce, attaining a recovery rate of 84.0% – 104.1%. From this work, it can be concluded that microfluidic sensing technology has potential for selective, sensitive, and complex-system analysis, thereby underpinning its applicability in food and environmental safety and providing on-site diagnostics.

In addition to electrochemical sensing, chemiresistive sensing has been used to detect heavy metals in water samples. In this direction, S. Mohanty and team (Mohanty et al., 2023) developed a portable, smartphone-enabled chemiresistive sensor using graphene oxide functionalized with the oligosaccharide β-cyclodextrin as the sensing material, which was drop-cast onto gold-coated copper μIDEs as a transducing agent, as shown in Fig. 10(c). While testing lead ions in tap water, a detection range of 100 pM to 10 μM was achieved, with a limit of detection as low as 100 pM, which is below the WHO permissible limits. Thus, this study opens a new door for integrating portable chemiresistive sensing with smartphones and ML-assisted analysis, applicable towards real-time heavy metal monitoring.

In summary, portable electrochemical devices have proven their worth by offering on-site detection with selectivity and sensitivity, paving the way for smart sensors. Despite this, challenges persist, including electrode fouling, matrix interference, limited long-term stability, and degradation of the sensing surface. This will require further standardization and large-scale validation before these portable sensors become comparable to established lab-based analytical tools. Furthermore, to enhance the practical applicability of these sensing techniques, the development of versatile sensors capable of simultaneously detecting multiple heavy metals in food matrices should be encouraged; such sensors should be modular and adaptable, with application-specific sensing interfaces. Lastly, integrating these portable devices into digital monitoring networks and policy-level food safety surveillance frameworks will reduce exposure to foodborne heavy metals.

7. Conclusion

Heavy metal contamination poses a serious threat to human health by affecting the food systems and the environment; accordingly, diagnostic tools must be developed to detect these toxins at trace levels with sensitivity and reliability.

This review critically analyzes current trends in electrochemical nanosensors for the detection of toxic metals, such as Pb^{2+}, Cd^{2+}, and Hg^{2+}, in various food matrices, including water, dairy products, seafood, and plant-based foods. Incorporating nanostructured materials significantly enhances electrochemical sensing characteristics by increasing the electrode surface area, improving electron transfer dynamics, and facilitating the effective adsorption of target metal ions at the electrode-surface interface. A relative comparison of reported detection limits indicates that hybrid nanocomposite systems typically exhibit greater analytical sensitivity than single-component nanomaterials. Frequently, sensors using graphene derivatives, noble metal nanoparticles, and metal-organic frameworks reach nanomolar (or below) detection limits. Matrix complexity, electrode modification strategies, and sample pretreatment procedures continue to have a potent effect on analytical performance. The presence of complex food matrices (e.g., milk, seafood, and plant tissues) can introduce matrix interferences that may affect sensor response and reproducibility.

Compared with conventional approaches such as ICP-MS, ICP-OES, and AAS, sensors often face challenges, including matrix interference, ambient moisture, and the complexity of food matrices, which impair their precision and the ability to differentiate among analytes. Electrochemical sensors for heavy metal detection face additional challenges, including electrode fouling, power limitations, calibration difficulties, signal drift, and long-term stability (degradation of the sensing surface) during extended use. To overcome these challenges, research should focus on developing antifouling surfaces that prevent unwanted substances from adhering, as well as on using hybrid sensing systems for smarter data analysis and signal processing.

A combination of electrochemical nanosensors and portable analytical platforms, microfluidic biosensing development platforms, and multiplexed multi-metal detection approaches will be necessary to enhance practical applications in food quality management. Lastly, through networking and the IoT-enabled integration of these portable devices into sensor networks, the creation of digital monitoring and food safety surveillance frameworks at the policy level will reduce exposure to foodborne heavy metals.

Declarations

Ethical Approval:

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Consent to Participate:

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The authors declare that they have no known competing interests that could have appeared to influence the work reported in this paper.

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V.S., A.Sa. and A.Sh. performed the literature review and drafted the manuscript. A.A. and G.A. contributed to data collection and figure preparation. K.K.A. and M.S.S. assisted in analysis and critical revision. A.K.T. and A.Si. supported data compilation and editing. K.A. contributed to conceptualization and overall guidance. H.P. supervised the work and finalized the manuscript. All authors approve the final version of the manuscript.

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Figures

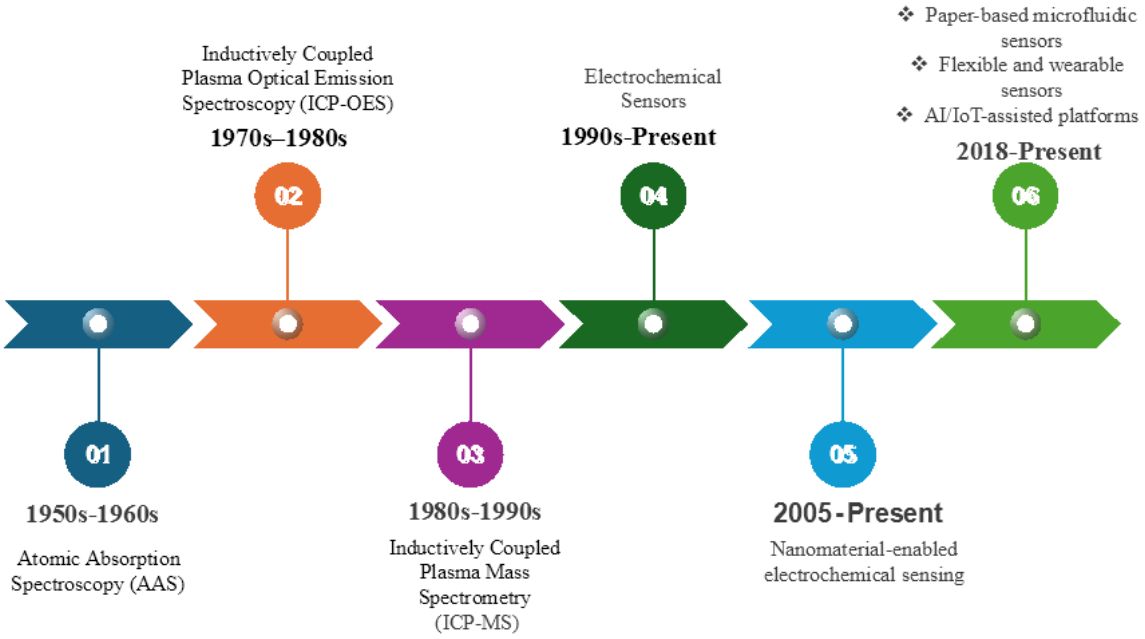

Figure 1

Evolution of technologies for heavy-metal detection in food matrices.

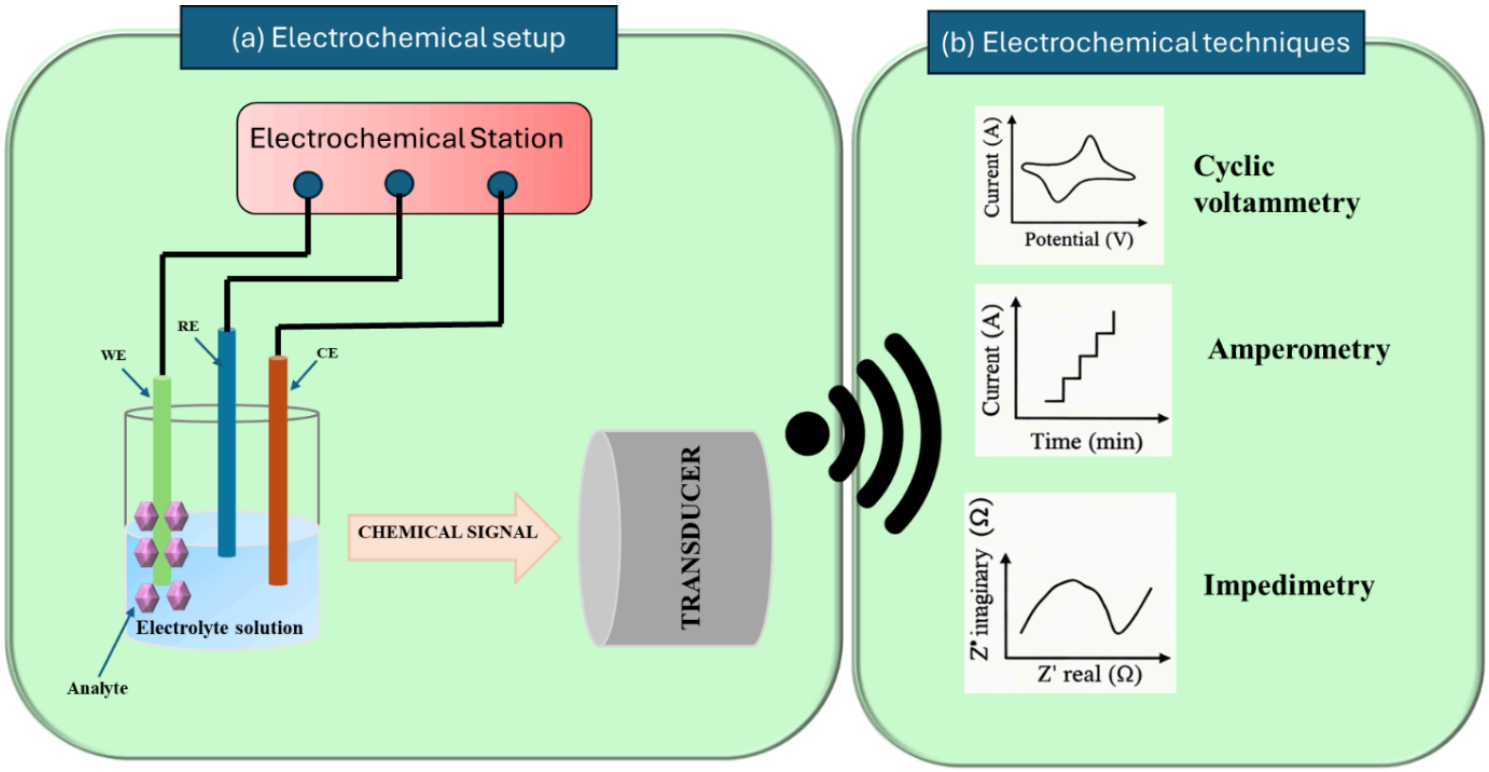

Figure 2

The core working principle of electrochemical sensing (a) Electrochemical setup (b) Electrochemical techniques.

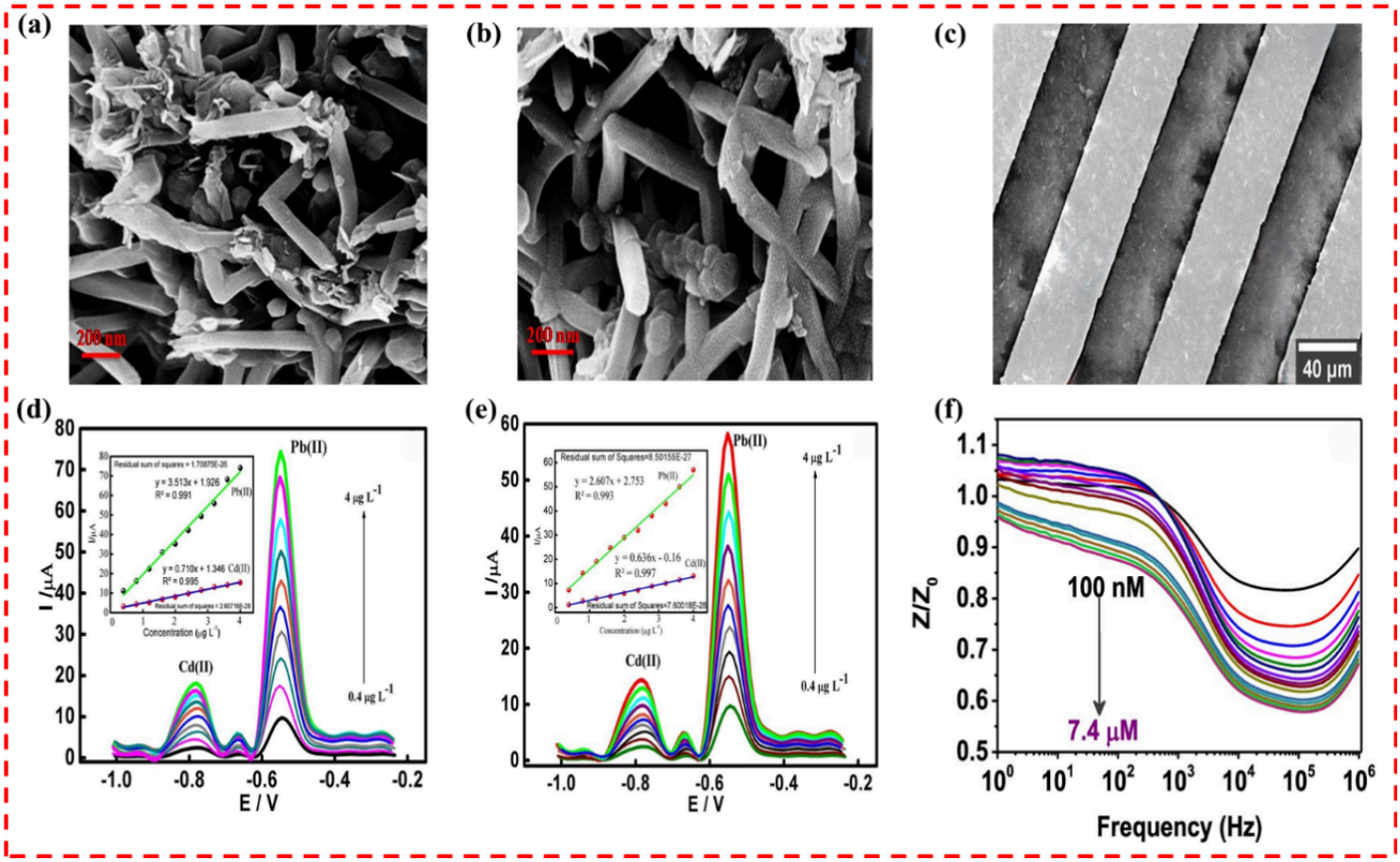

Figure 3

FESEM image of (a) MWCNT/Hyalu/l-Ser, (b) MWCNT/Hyalu/l-Cys, (d) Sensing of Cd(II) and Pb(II) obtained from A-MWCNT/Hyalu/l-Cys/GCE, (e) Sensing obtained from A-MWCNT/Hyalu/l-Ser/GCE in the concentration range of 0.4 to 4 µg L^{-1} in 0.1 M HAc–NaAc (pH 4.5). Reproduced with permission from (Priya et al., 2020), Copyright (2020) Elsevier; (c) zoomed view of SEM image of PEI-CNT/GO on Au IDE, (f) Relative impedance modulus (Z/Z_0) v/s frequency of the PEI-CNT/GO layer-by-layer film. Reproduced with permission from (Martinez Jimenez et al., 2021), Copyright (2021) American Chemical Society.

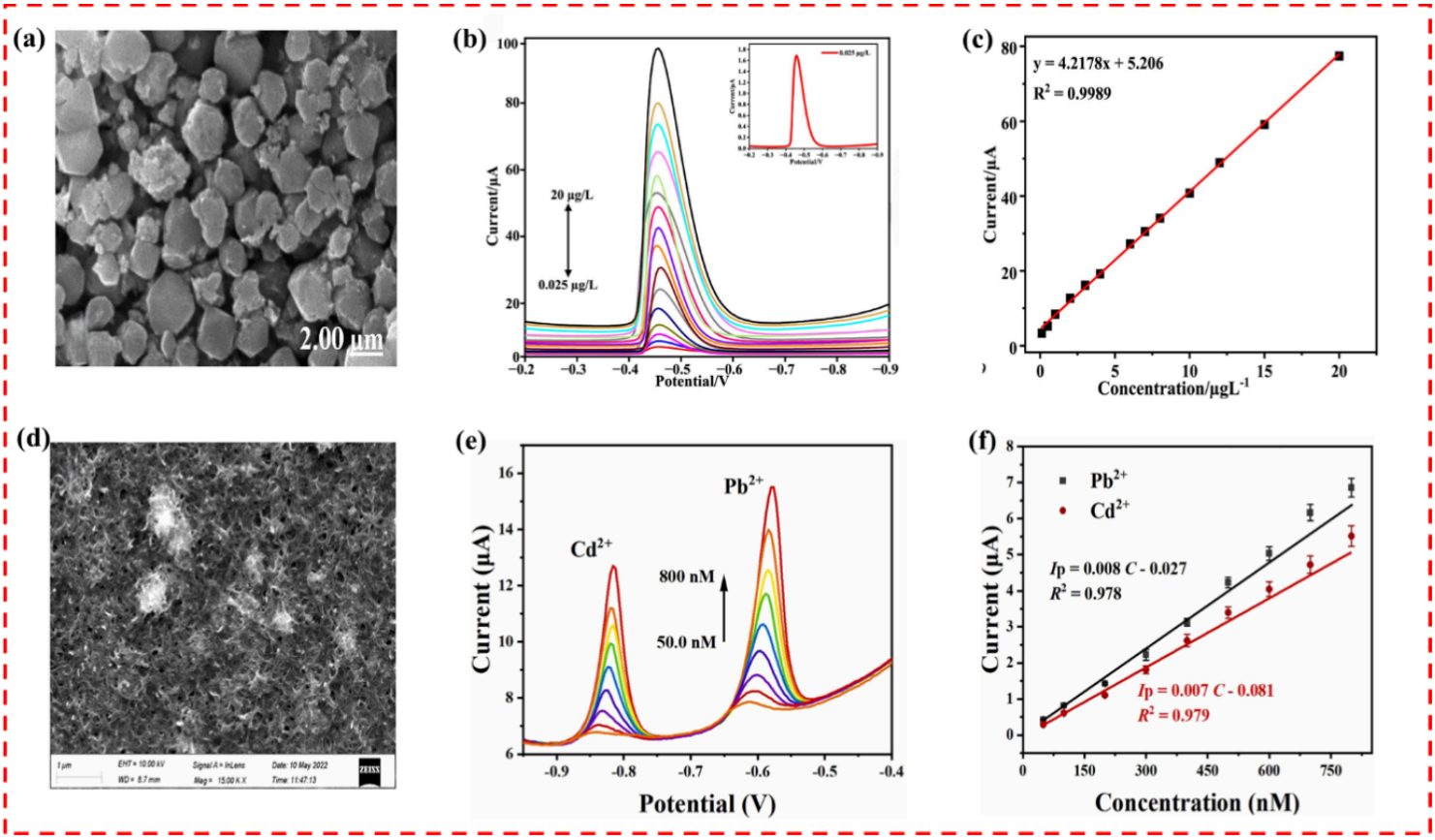

Figure 4

(a) SEM image of PANI@Bi-MOF, (b) DPASV response of PANI@Bi-MOF/GCE towards different concentrations of Pb^{2+} (0.5 μgL^{-1} to 20 μgL^{-1}), (c) Correlation between peak current and Pb^{2+} concentration. Reproduced with permission (Saleem et al., 2025), Copyright (2025) Elsevier; (d) SEM image of Bi/ZIF-8-NH_2/CNTs, (e) DPASV response towards simultaneous detection of Pb^{2+} and Cd^{2+}, (f) linear relationship with concentrations in the range of 0.050 ~ 0.800 µM. Reproduced with permission (X. Chen et al., 2023), Copyright (2023) Elsevier.

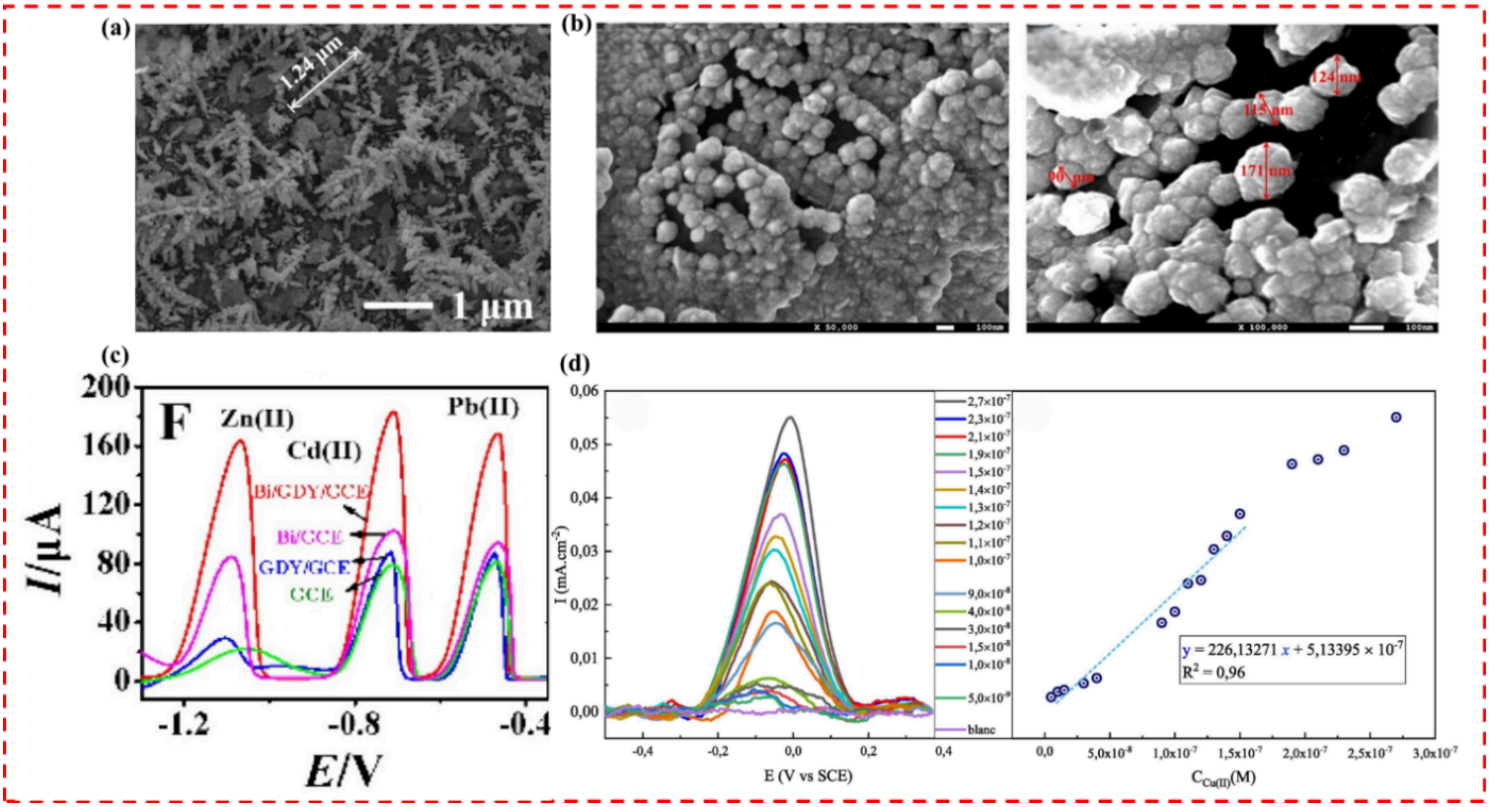

Figure 5

(a) SEM image of Bi/GDY/GCE, (c) DPASV curves in 100.0 μM Zn(II), Cd(II), and Pb(II) mixture solution on different modified electrodes. Reproduced with permission from (Ai et al., 2023), Copyright (2023) Elsevier; (b) SEM images of NiO-nanoparticles/GrE modified electrode, (d) SWASV curves of Cu(II) at different concentrations from 5×10^{-9} to 2.7×10^{-7} M on NiO-nanoparticles/GrE under optimum conditions: pH 3.0; deposition potential: –0.6 V; deposition time: 420 s; quiet time: 30 s, frequency: 90 Hz, pulse amplitude: 90 mV; and step increment: 4 mV, and the calibration plot. Reproduced with permission from (Moussaoui et al., 2023), Copyright (2023), Elsevier.

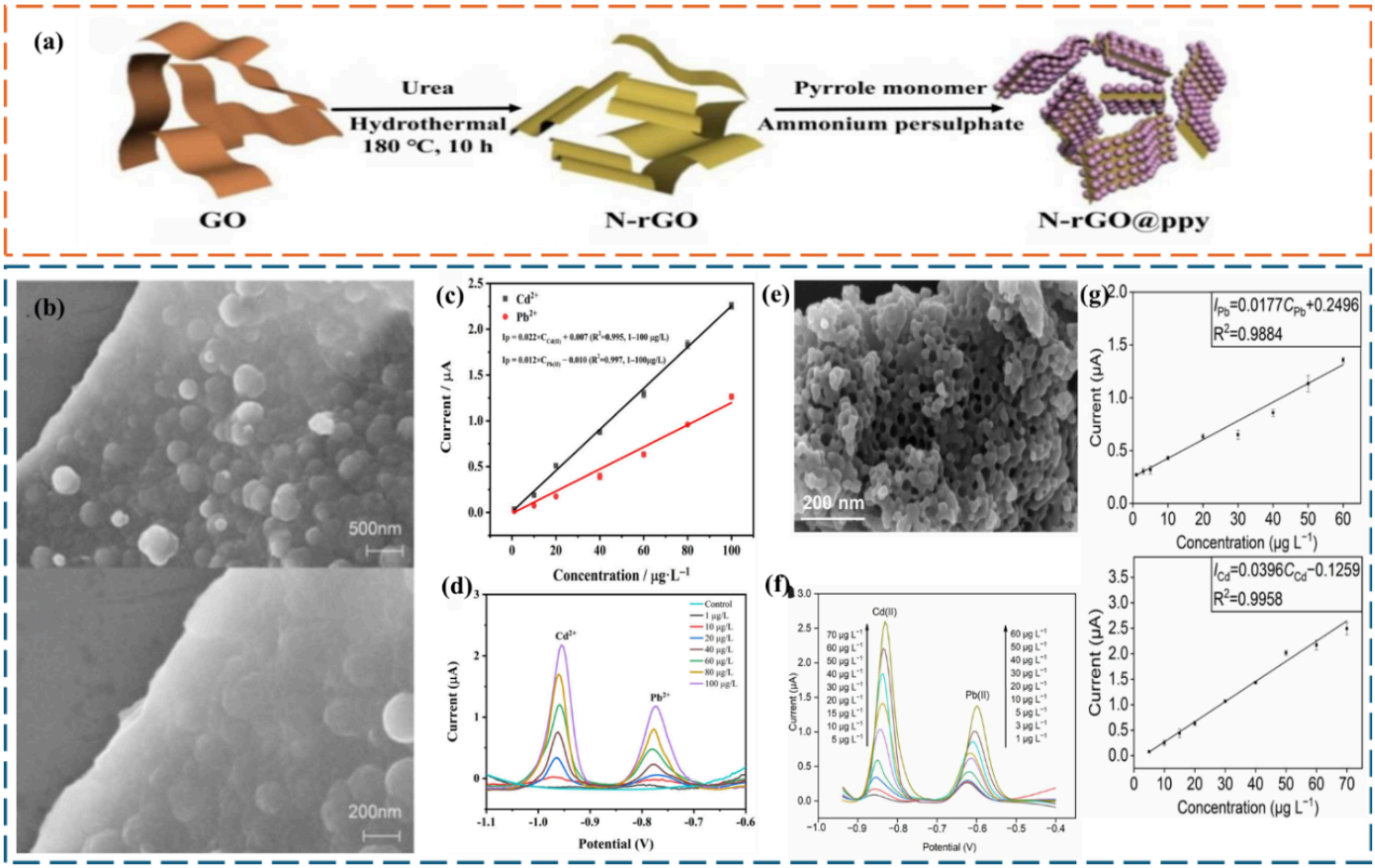

Figure 6

(a) Schematic of the synthesis procedure of N-rGO@ppy, (b) SEM image of N-rGO@ppy, (c) Calibration curves for concentrations of 1–100 μg L^{-1}, (d) SWASVs of simultaneous detection of Pb^{2+} and Cd^{2+} at different concentrations on N-rGO@ppy/SPE. Reproduced with permission (F. Wang et al., 2025), Copyright 2025 MDPI; (e) SEM image of nanoporous carbon, (f) Stripping voltammograms of the SPE/NPC for Pb(II) and Cd(II) with various concentrations in acetic acid buffer solution with 0.81 mg L^{-1} Bi(III), (g) The calibration plots of Pb(II) and Cd(II) respectively. Reproduced with permission (H. Chen et al., 2023), Copyright (2023) MDPI.

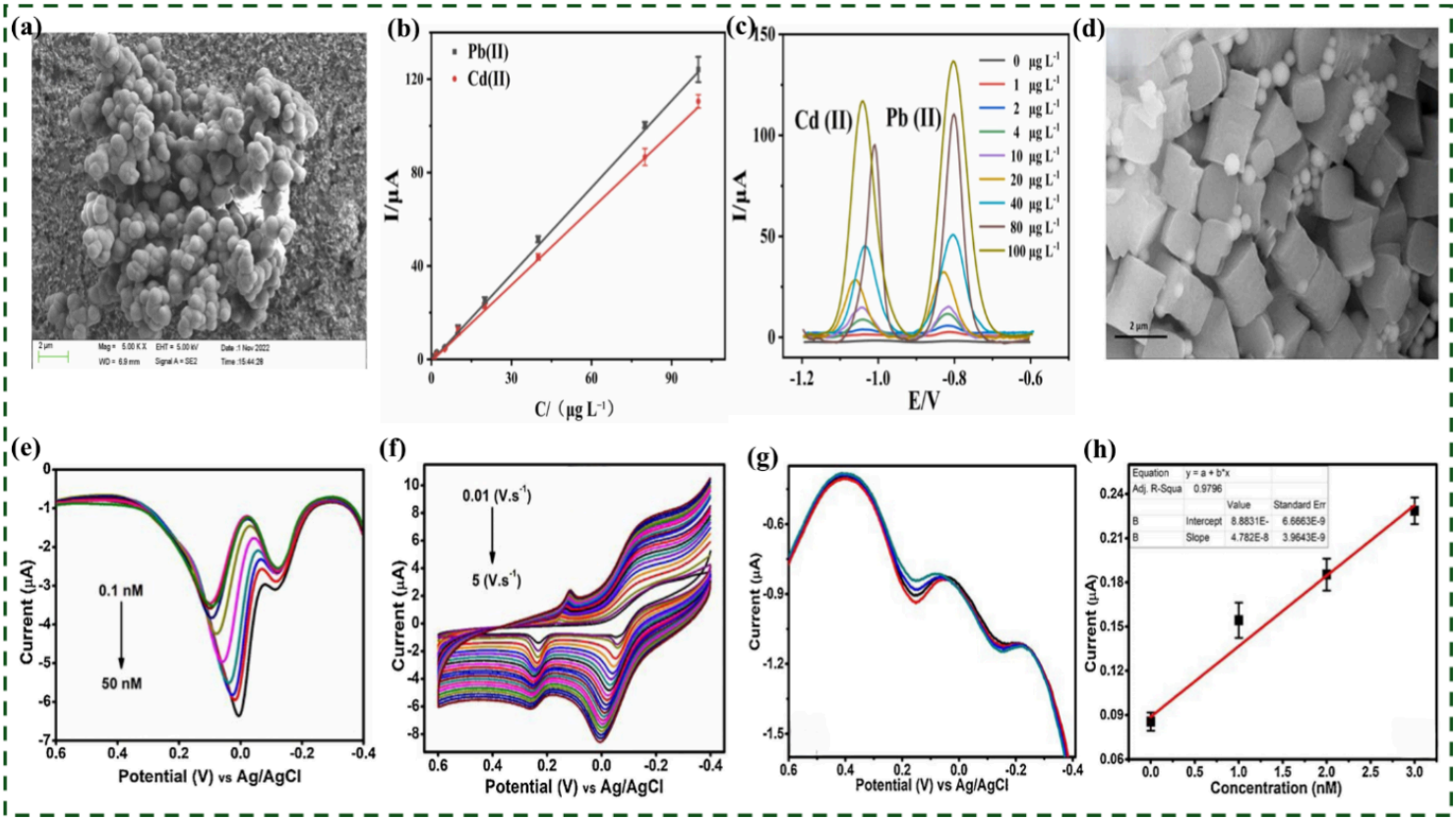

Figure 7

(a) SEM image of CMP/BiNPs/SPCE, (b) Plots of peak currents vs concentration (Electrodeposition was carried out at −1.4 V for 300 s), (c) Stripping voltammograms of CMP/BiNPs/SPCE with different concentrations of ternary mixture of Pb(II) and Cd(II) (0, 1, 2, 4, 10, 20, 40, 80, and 100 μg L^{-1}, respectively). Reproduced with permission from (Huang et al., 2024), Copyright (2024) Elsevier. (d) SEM image of Cu-MOF nanoparticles, (e) DPV voltammograms with the varying concentrations of Hg^{2+} (0.1 to 50 nM) in 0.1 M PBS of pH 9.0, (f) CV at scan rates from 0.01 to 5 $V.s^{-1}$ for Cu-MOF modified electrode, (g) and (h) The electrochemical sensor was used for the assay of Hg^{2+} in sample matrices of tuna fish. Reproduced with permission from (Singh et al., 2020), Copyright (2020) Elsevier.

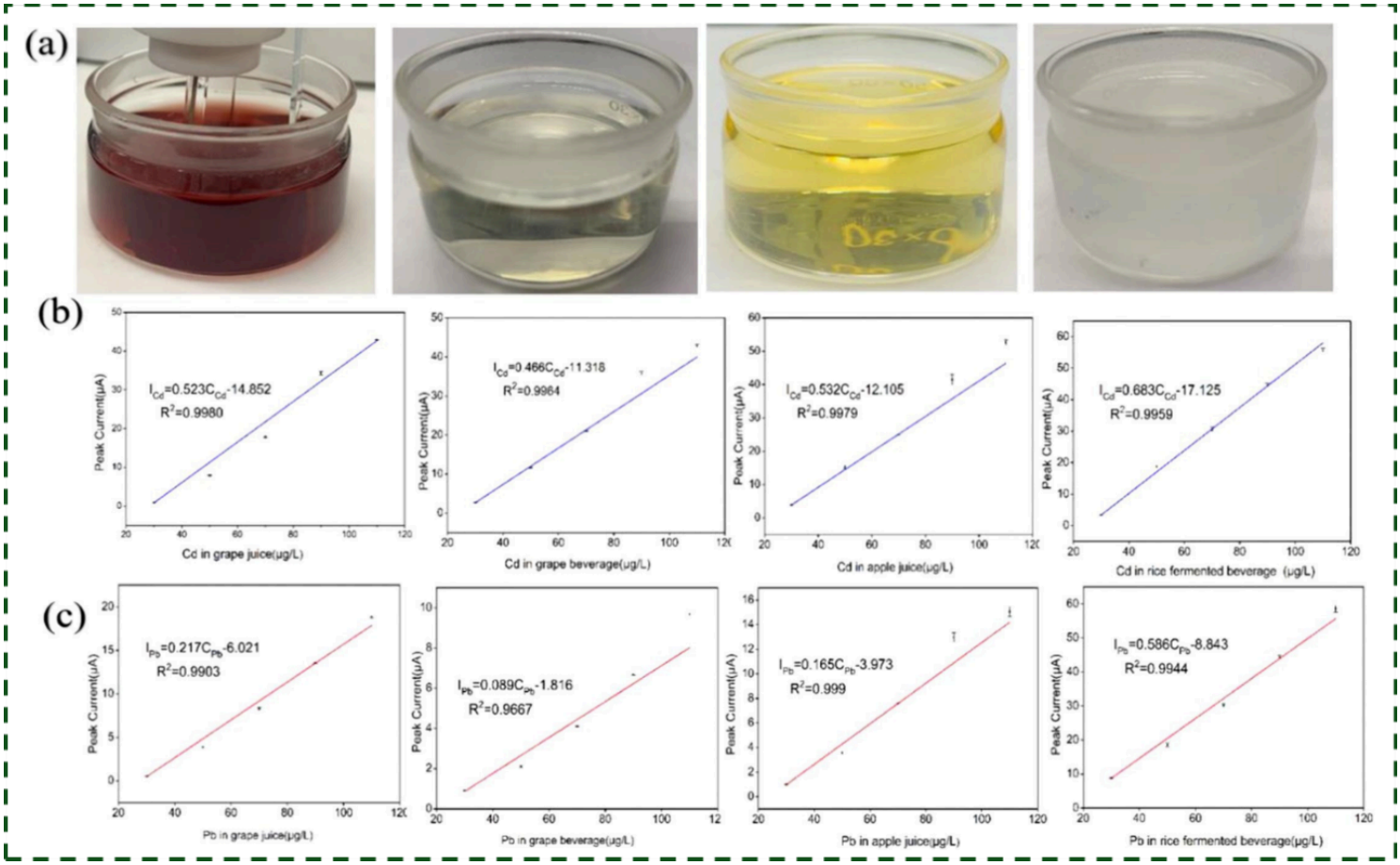

Figure 8

(a) Photograph of direct electrochemical detection in grape juice, grape beverage, apple juice, rice fermented beverage using p-PDMS@MSF/ITO electrode. (b) The working curve of Cd^{2+}detection by p-PDMS@MSF/ITO electrodes in juice and beverage samples (n = 3). (c) The working curve of Pb^{2+}detection by p-PDMS@MSF/ITO electrodes in juice and beverage samples (n = 3). Reproduced with permission from (G. Li et al., 2021), Copyright (2021) Elsevier.

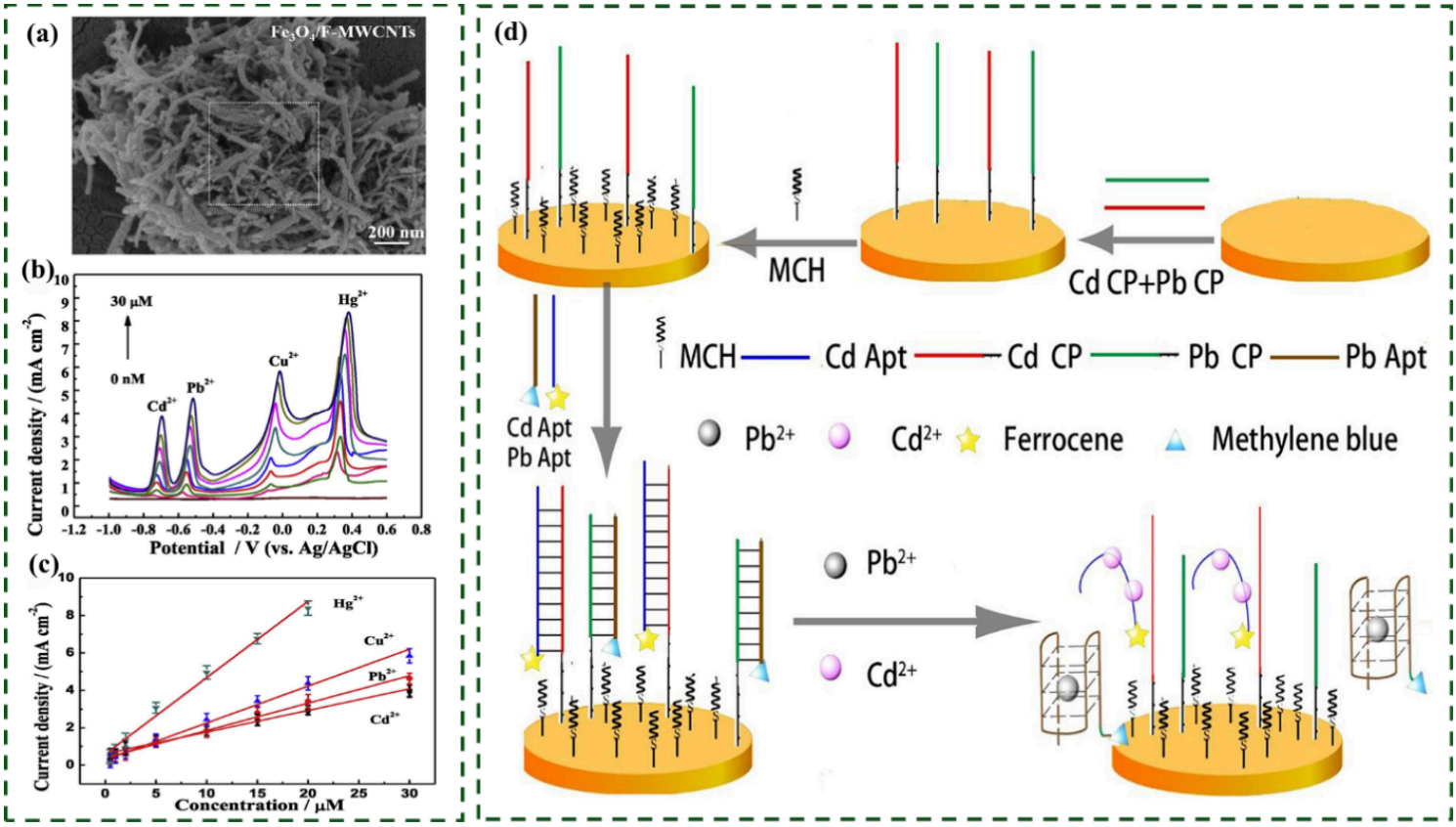

Figure 9

(a) SEM image of Fe_3O_4 nanoparticles + fluorinated MWCNT, (b) SWASV Fe_3O_4/F-MWCNTs for the simultaneous assay of Cd^{2+}, Pb^{2+}, Cu^{2+}, and Hg^{2+} (from bottom to top: 0 nM, 50 nM, 250 nM, 500 nM, 1 μM, 2 μM, 5 μM, 10 μM, 15 μM, 20 μM, and 30 μM), (c) calibration plots of Fe_3O_4/F-MWCNTs (n = 3). Reproduced with permission from (Wu et al., 2019), Copyright (2019) Elsevier; (d) Schematic illustration of an electrochemical aptasensor for the detection of Cd^{2+} and Pb^{2+}. Reproduced with permission from (Yuan et al., 2022), Copyright (2022) Elsevier.

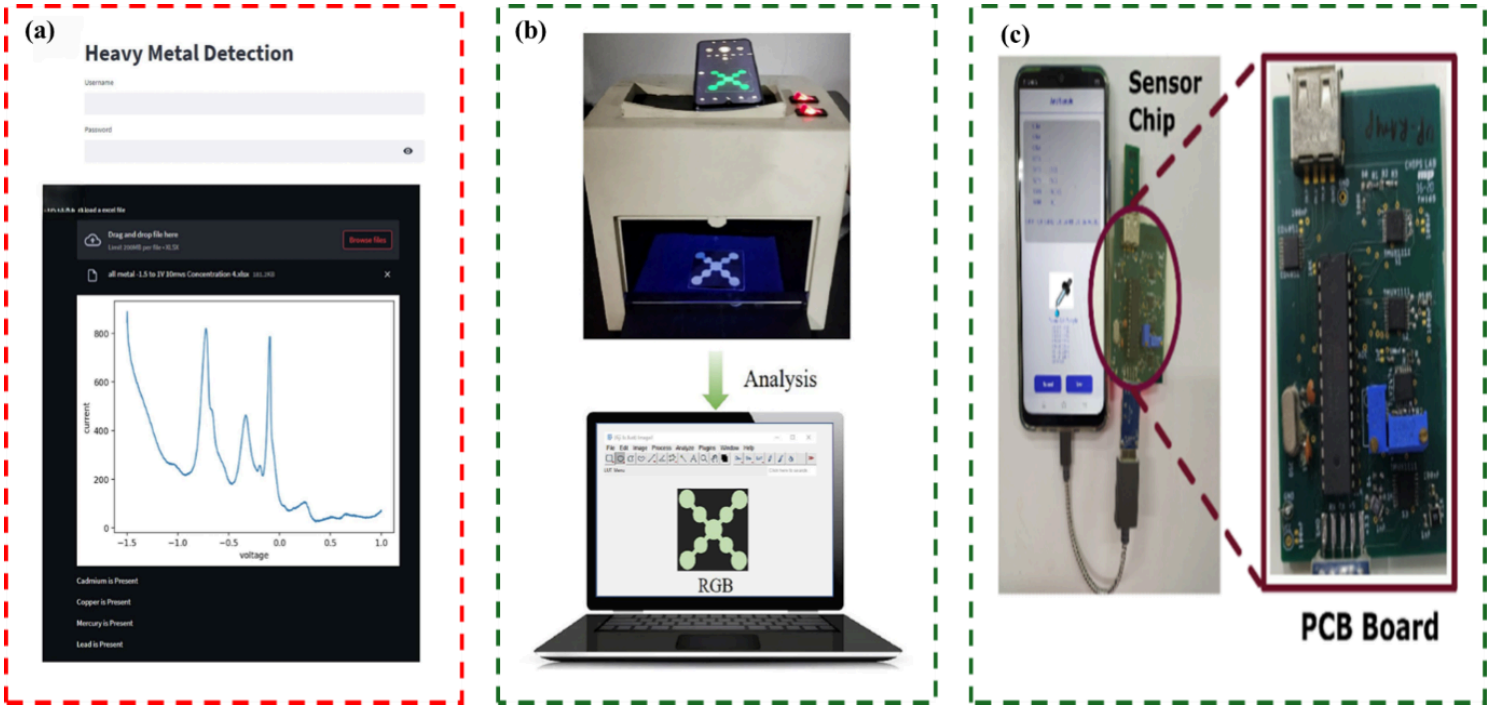

Figure 10

(a) Integration of IoT with the developed heavy metal sensor and a user-friendly web interface. Reproduced with permission from (Lahari et al., 2025), Copyright (2025) Springer Nature; (b) Detection device and photograph of the multi-channel fluorescent paper-based chip. Reproduced with permission from (Yuan et al., 2024), Copyright (2024) Elsevier; (c) Developed readout circuit board and Android application interfaced with sensor chip for data collection. Reproduced with permission from (Mohanty et al., 2023), Copyright (2023) Elsevier.

Supplementary Files

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- floatimage1.png