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MODERN ANALYTICAL APPROACHES FOR THE DETECTION AND QUANTITATIVE ANALYSIS OF HEAVY METALS IN ENVIRONMENTAL MATRICES

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ABSTRACT

Heavy metal contamination of environmental matrices including water, soil, sediment, and biological specimens, constitutes a pervasive public health and ecological concern of global magnitude. The accurate detection and quantitative determination of heavy metals are indispensable for environmental monitoring, risk assessment, and regulatory compliance. This review critically appraises modern analytical strategies employed for heavy metal analysis across diverse environmental matrices. Classical techniques including flame atomic absorption spectrometry (FAAS), graphite furnace atomic absorption spectrometry (GFAAS), inductively coupled plasma-optical emission spectrometry (ICP-OES), and inductively coupled plasma-mass spectrometry (ICP-MS) are evaluated alongside emerging approaches such as laser-induced breakdown spectroscopy (LIBS), portable X-ray fluorescence (pXRF), electrochemical sensors, and aptamer-based biosensors. Special attention is accorded to sample preparation strategies, multi-element analysis capabilities, detection limits, matrix interferences, and green analytical chemistry considerations. The comparative strengths and limitations of each technique are discussed in the context of their field and laboratory applicability. The review further highlights the integration of nanomaterials, machine learning algorithms, and miniaturised platforms as transformative innovations enhancing sensitivity, selectivity, and throughput. Prospects for point-of-care and real-time environmental monitoring are identified, with implications for low-resource settings such as those encountered in sub-Saharan Africa.

KEYWORDS: heavy metals; environmental matrices; ICP-MS; electrochemical sensors; LIBS; atomic absorption spectrometry; XRF; biosensors; nanomaterials; environmental monitoring.

1. INTRODUCTION

Heavy metals are naturally occurring elements with an atomic density greater than 5 g/cm³ and atomic numbers above 20, many of which exhibit significant toxicity even at trace concentrations.[1] Elements such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), copper (Cu), zinc (Zn), and nickel (Ni) are widely distributed across environmental matrices as a consequence of both geogenic processes and anthropogenic activities including mining, smelting, electroplating, agricultural application of phosphate fertilisers, industrial discharge, and vehicular emissions.[1,2] Unlike organic pollutants, heavy metals are non-biodegradable and undergo bioaccumulation and biomagnification through food chains, resulting in

chronic and acute toxicological consequences in humans and ecosystems.[3]

The World Health Organization (WHO) has established permissible limits for key heavy metals in drinking water, recognising their documented roles in neurotoxicity, nephrotoxicity, carcinogenesis, and cardiovascular disease.[4,5] For instance, exposure to Pb at levels exceeding 10 µg/L in drinking water has been associated with irreversible neurological deficits in children, while Cd accumulation causes renal tubular dysfunction and skeletal demineralisation.[4] The magnitude of health burden associated with heavy metal contamination necessitates robust, sensitive, and reliable analytical methodologies capable of detecting metals at part-per-billion (ppb) and part-per-trillion (ppt) concentrations across complex environmental matrices.

Environmental matrices present substantial analytical challenges owing to their heterogeneous composition. Soil and sediment samples contain silica, clay minerals, organic matter, and co-extractable interferents; water matrices vary widely in salinity, hardness, and dissolved organic carbon content; while biological specimens (plants, blood, urine) require careful destruction of the organic matrix before metal quantification.[6,7] Against this backdrop, the past five years have witnessed remarkable advances in analytical instrumentation, sensor design, and hyphenated techniques that have substantially improved the capacity for heavy metal surveillance.

This review provides a comprehensive and critical appraisal of modern analytical methodologies for heavy metal detection and quantification in environmental matrices, encompassing conventional spectroscopic platforms, emerging spectroscopic techniques such as LIBS, electrochemical sensing approaches, optical biosensors, and portable field-deployable systems. The review further addresses sample preparation strategies, greenness assessment, and the integration of chemometric and artificial intelligence tools. Table 1 summarises the Comparative overview of analytical techniques for heavy metal detection in environmental matrices: key performance parameters., while Figure 1 presents the Generalised analytical workflow for heavy metal determination in environmental matrices, from sample collection and preparation to detection and data reporting.

Table 1: Comparative overview of analytical techniques for heavy metal detection in environmental matrices: key performance parameters.

Technique	Detection Limit	Matrix Applicability	Sensitivity	Cost	Key Reference
FAAS	µg/L range	Water, soil, food	Moderate	Low	[6,7]
GFAAS/ET-AAS	ng/L range	Biological, water, soil	High	Moderate	[2,7]
ICP-OES	µg/L–ng/L	Multi-matrix	High	Moderate	[8,9]
ICP-MS	ng/L–pg/L	All environmental matrices	Very High	High	[9]
ED-XRF	mg/kg range	Soil, sediment, plant	Moderate	Moderate	[17,18]
LIBS	mg/kg range	Soil, plant, sediment	Moderate	Moderate–High	[13,14,15]
Electrochemical	ng/L–µg/L	Water, wastewater	High	Low	[10,11,12]
Optical Biosensor	ng/L range	Water, biological	High	Low–Moderate	[20,21]

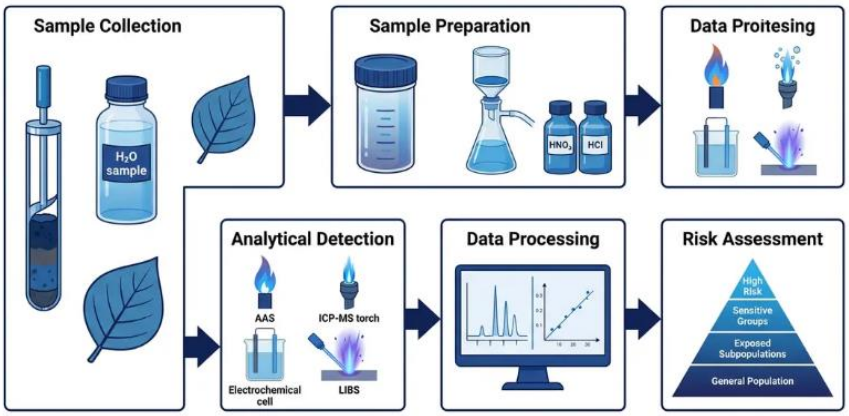

Figure 1: Generalised analytical workflow for heavy metal determination in environmental matrices, from sample collection and preparation to detection and data reporting.

Caption: A clean scientific flowchart diagram with five sequential stages connected by directional arrows on a white background: (1) 'Sample Collection' icon – soil core, water bottle, and plant leaf; (2) 'Sample Preparation' icon, microwave digestion vessel and filtration funnel with acid bottles; (3) 'Analytical Detection' icon – split into four instrument icons: AAS flame, ICP-MS torch, electrochemical cell, and LIBS laser beam; (4) 'Data Processing' icon, computer screen showing chromatogram and calibration curve; (5) 'Risk Assessment' icon – environmental health pyramid.

Sources: Authors illustrations adapted from references.[6,7,20]

2. Environmental Matrices and Heavy Metal Contamination

Heavy metal contamination spans a spectrum of environmental matrices, each imposing distinct physicochemical challenges on analytical procedures. Water matrices, comprising surface water, groundwater, seawater, and wastewater, are the most commonly surveyed due to direct implications for human drinking water safety and aquatic ecosystem integrity.[3,5] Soil and sediment matrices serve as long-term reservoirs for heavy metals deposited through industrial fallout, agricultural inputs, and atmospheric deposition.[1] The distribution and speciation of metals in these matrices are governed by pH, redox potential, organic matter content, and microbial activity, collectively determining their bioavailability and leaching potential.[3]

Biological matrices, including plant tissues, animal organs, blood, urine, and hair, serve as critical bioindicators for evaluating human and ecosystem exposure to heavy metals.[6] Plants bioaccumulate metals from contaminated soils and irrigation water, rendering food crop analysis an essential component of dietary exposure assessment.[6,7] Table 2 summarises the key heavy metals of environmental and public health significance, their WHO permissible limits in drinking water, principal health effects, and the environmental matrices in which they are typically determined.

Table 2: Priority heavy metals: WHO permissible limits in drinking water, key health effects, and principal environmental matrices.

Heavy Metal	WHO Limit (µg/L)	Key Health Effects	Principal Matrices	Reference
Lead (Pb)	10	Neurotoxicity, anaemia, renal damage, cardiovascular effects	Water, soil, blood, food	[1,4]
Cadmium (Cd)	3	Renal tubular dysfunction, bone demineralisation, carcinogenesis	Soil, water, food, urine	[1,5]
Mercury (Hg)	6	Neurotoxicity, renal damage, immune dysfunction	Water, fish, blood	[2,5]
Arsenic (As)	10	Skin lesions, carcinogenesis, cardiovascular disease	Water, food, soil	[3,4]
Chromium (Cr)	50	Carcinogenesis (Cr VI), hepatotoxicity, skin irritation	Water, soil, effluent	[1,2]
Copper (Cu)	2000	Hepatic cirrhosis, gastrointestinal irritation, Wilson's disease	Water, soil, sediment	[3]
Zinc (Zn)	—	Respiratory distress (excess), essential at low levels	Soil, water, food	[1]
Nickel (Ni)	70	Allergic dermatitis, carcinogenesis (Ni compounds)	Water, soil, food	[2,4]

3. Conventional Spectroscopic Techniques

3.1 Atomic Absorption Spectrometry (AAS)

Atomic absorption spectrometry (AAS) remains the most widely deployed technique for single-element heavy metal determination in environmental matrices, attributable to its simplicity, robustness, and relatively low capital cost.[6,7] In flame AAS (FAAS), the atomisation of metal ions occurs within an air-acetylene or nitrous oxide-acetylene flame, offering detection limits in the µg/L range suitable for moderately contaminated samples. Graphite furnace AAS (GFAAS, also termed electrothermal AAS or ET-AAS) achieves substantially lower detection limits in the ng/L range through electrothermal atomisation in a graphite tube, enabling trace-level determinations in complex biological and environmental matrices.[2,7]

Key operational advantages of AAS include element specificity via wavelength selection using hollow cathode lamps, good precision (RSD typically <3%), and

compatibility with matrix modifiers that suppress interferences. However, limitations include sequential (rather than simultaneous) multi-element capability, susceptibility to background absorption requiring Zeeman or deuterium correction, and the need for prior wet digestion of solid matrices.[7] Cold vapour AAS (CV-AAS) and hydride generation AAS (HG-AAS) provide sub-µg/L detection limits specifically for Hg and hydride-forming elements (As, Se, Sb), respectively, and remain analytically indispensable for these species in water and sediment.[2]

3.2 Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) and ICP-Mass Spectrometry (ICP-MS)

ICP-OES and ICP-MS represent the current gold standards for multi-element heavy metal analysis in environmental matrices, offering simultaneous determination of 30–70 elements within a single analytical run.[8,9] In ICP-OES, sample solutions are nebulised into an argon plasma (~6,000–10,000 K) where excitation of atomic emission lines occurs; spectral resolution by CCD or Echelle spectrometers enables simultaneous multi-element quantification with detection limits in the µg/L to low ng/L range.[8] The introduction of axially viewed configurations and high-resolution spectrometers has further extended sensitivity and reduced spectral interferences.

ICP-MS achieves detection limits two to three orders of magnitude lower than ICP-OES (sub-ng/L to pg/L range) through mass spectrometric discrimination of elemental ions based on mass-to-charge ratio, enabling ultra-trace analysis of Pb, Cd, Hg, As, and rare earth elements in environmental matrices.[9] The technique is susceptible to polyatomic isobaric interferences (e.g., $^{40}Ar^{35}Cl^{+}$ interfering with $^{75}As^{+}$) that are effectively resolved by collision/reaction cell technology and sector-field ICP-MS instruments. Hyphenated systems coupling chromatographic separation (IC, HPLC, GC) with ICP-MS enable chemical speciation analysis, distinguishing, for instance, As(III) from As(V) or Cr(III) from Cr(VI), a critical capability for risk assessment given that toxicity is species-dependent.[8]

4. X-Ray Fluorescence (Xrf) Spectrometry

X-ray fluorescence (XRF) spectrometry provides a rapid, non-destructive approach to simultaneous multi-element analysis of solid matrices including soil, sediment, geological materials, and plant tissue.[17] Upon irradiation with primary X-rays, inner-shell electrons are ejected and characteristic fluorescent X-rays emitted as outer-shell electrons fill the vacancies; detection and wavelength/energy discrimination of these emissions yield element-specific signals proportional to concentration.[17] Wavelength-dispersive XRF (WD-XRF) offers superior spectral resolution and lower detection limits (1–10 mg/kg range for most heavy metals), while energy-dispersive XRF (ED-XRF) provides faster analysis with acceptable sensitivity for environmental screening.[17]

Portable XRF (pXRF) instruments have transformed in-situ environmental surveillance by enabling real-time, on-site screening of soil contamination without sample transport or laboratory preparation.[18] Yang et al.[17] demonstrated that ED-XRF coupled with principal component analysis (PCA) and support vector regression yielded reliable quantification of multiple heavy metals in agricultural soil ($R^2 > 0.93$). Qu et al.[18] reported that in-situ pXRF, corrected for matrix effects using geographically weighted regression, achieved high-precision spatial mapping of soil heavy metals across a regional scale (RI = 83.74%). Tepanosyan et al.[19] established the comparability of pXRF data with ICP-MS reference values for contaminated urban soils, noting that pXRF is most reliable for elements above 50 mg/kg. Limitations include lower sensitivity compared to ICP-MS and susceptibility to matrix moisture and particle size effects on signal intensity.[19,24]

5. Laser-Induced Breakdown Spectroscopy (Libs)

LIBS has emerged as a highly versatile, rapid technique for elemental analysis of solid, liquid, and gaseous phases, requiring minimal or no sample preparation and enabling real-time, stand-off, and in-situ measurements.[14,16,23] In LIBS, a focused high-power pulsed laser ablates a microscopic volume of the sample surface, generating a microplasma that emits characteristic atomic emission lines upon cooling.[14,23] Simultaneous multi-element detection, including light elements (C, N, H) inaccessible to XRF, and applicability to all sample states are key operational advantages.

Yang et al.[14] reviewed signal enhancement strategies for agricultural LIBS applications, demonstrating that double-pulse LIBS, resonance-enhanced LIBS (RELIBS), and spark-discharge assisted LIBS significantly lowered detection limits for Cd and Pb in soil to sub-mg/kg levels. Ma et al.[15] validated portable LIBS instrumentation for in-field detection of Cd and Pb in soil, achieving LODs of 0.8 mg/kg and 2.3 mg/kg respectively, demonstrating field-deployable capability. Ren et al.[16] reviewed LIBS applications across soil, water, and crop matrices in agriculture, highlighting the synergy between LIBS and machine learning algorithms (PLS, ANN, SVM) for quantitative accuracy improvement. Khan et al.[23] catalogued trace element detection limits achieved across various LIBS configurations, emphasising the coupling of LIBS with pre-concentration techniques and confined geometries to enhance sensitivity for sub-mg/kg determinations in environmental matrices. Figure 2 shows the Schematic diagram of a typical LIBS system for heavy metal detection in soil and environmental samples, illustrating laser pulse delivery, plasma generation, spectral acquisition, and data processing pipeline

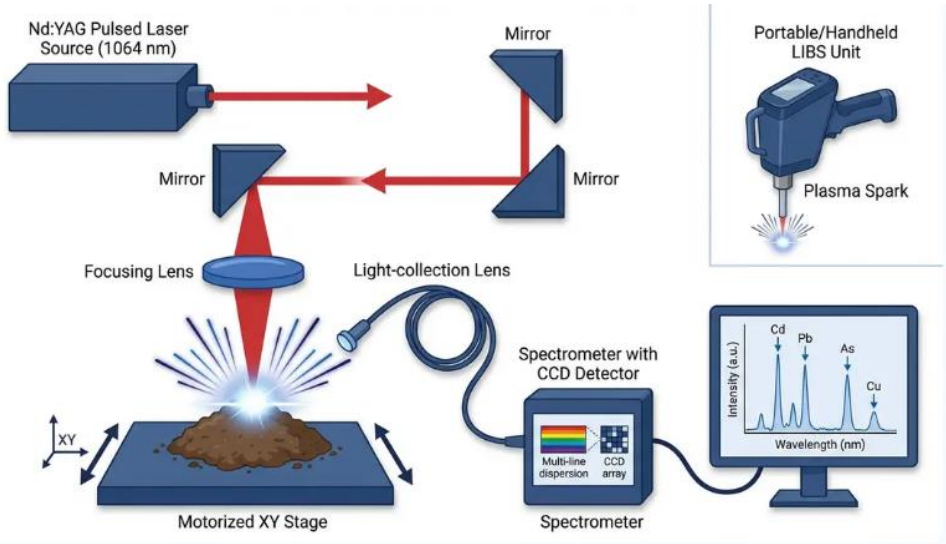

Figure 2: Schematic diagram of a typical LIBS system for heavy metal detection in soil and environmental samples, illustrating laser pulse delivery, plasma generation, spectral acquisition, and data processing pipeline.

Caption: A professional scientific schematic diagram on a white background showing the components of a LIBS (Laser-Induced Breakdown Spectroscopy) system: (1) Nd: YAG pulsed laser source emitting a beam (red arrow) directed by mirrors; (2) focusing lens concentrating the beam onto a soil sample on a motorised XY stage; (3) bright plasma spark above the sample surface with emission lines fanning outward; (4) fibre optic cable collecting emitted light; (5) spectrometer with CCD detector; (6) computer monitor displaying an atomic emission spectrum with labelled peaks for Cd, Pb, As, Cu. Include a sidebar showing portable/handheld LIBS unit.

Sources: Adapted from references.[14,15,16]

6.1 Principles and Configurations

Electrochemical techniques have experienced transformative development for heavy metal detection in water and wastewater matrices, offering excellent sensitivity, low cost, portability, and compatibility with on-site monitoring platforms.[10,11] The most widely employed electrochemical methods include stripping voltammetry (anodic/cathodic stripping: ASV, CSV; square-wave and differential pulse variants: SWASV, DPASV), differential pulse voltammetry (DPV), and electrochemical impedance spectroscopy (EIS).[10,12] In stripping voltammetry, target metal ions are pre-concentrated onto a modified electrode surface during a deposition step before being stripped back by a potential scan, yielding sharp oxidation peaks proportional to metal concentration, an inherent pre-concentration step that confers sub-µg/L detection limits.[10]

6.2 Nanomaterial-Modified Electrodes

Electrode surface modification with nanomaterials has dramatically enhanced the analytical performance of electrochemical sensors for heavy metal detection.[11,13] Carbon-based nanomaterials, including reduced graphene oxide (rGO), multi-walled carbon nanotubes (MWCNTs), graphene quantum dots, and bismuth film electrodes, provide large electroactive surface areas, enhanced electron transfer kinetics, and improved metal ion adsorption capacity.[13] Dinu Iacob et al.[13] demonstrated that sensors based on Fe_3O_4 nanoparticles and carbonaceous nanomaterials achieved simultaneous detection of Cd^{2+}, Pb^{2+}, Cu^{2+}, and Hg^{2+} at LODs of 0.01–0.08 µg/L in water samples, substantially below WHO permissible limits.

Ion-imprinted polymers (IIPs) represent a highly selective recognition strategy wherein polymer matrices are synthesised around a target metal ion template, leaving complementary cavities upon template removal that exhibit selective re-binding.[12,22] Sala et al.[12] comprehensively reviewed IIP-modified electrochemical sensors, demonstrating excellent selectivity for Cr(III), Pb(II), and Cu(II) in the presence of potentially interfering metal ions. Yu et al.[11] surveyed nanomaterial-based IIP electrochemical sensors, reporting LODs in the 0.001–0.1 µg/L range for multiple target metals. Table 3 provides a comparative overview of electrode materials, target analytes, LODs, and detection techniques for recently reported electrochemical sensors.

Table 3: Electrode materials, target analytes, achieved LODs, and electrochemical techniques for heavy metal detection sensors reported in recent literature.

Electrode Material	Target Metal(s)	LOD Achieved	Technique Used	Reference
Reduced graphene oxide (rGO)	Pb^{2+}, Cd^{2+}	0.02 µg/L	SWASV	[12]
Carbon nanotube (CNT) composites	Hg^{2+}, Cu^{2+}	0.05 µg/L	DPV	[13]
Fe_3O_4/carbonaceous nanomaterials	Cd^{2+}, Pb^{2+}, Cu^{2+}, Hg^{2+}	0.01–0.08 µg/L	SWASV	[13]
Ion-imprinted polymers (IIP)	Cr^{3+}, Pb^{2+}	0.03 µg/L	CV/DPV	[12]
Bismuth film electrodes	Pb^{2+}, Cd^{2+}, Zn^{2+}	0.1 µg/L	DPASV	[10]
MoS_2 nanosheet modified SPE	Pb^{2+}, Hg^{2+}	0.01 µg/L	DPV	[10]
Gold nanoparticle aptasensor	Pb^{2+}, Cd^{2+}	0.001 µg/L	EIS	[21]
Screen-printed electrodes (SPE)	Multiple metals	Variable	SWASV/DPV	[10]

6.3 Aptamer-Based Biosensors

Aptamers; synthetic single-stranded oligonucleotides selected by SELEX to bind specific targets with high affinity and selectivity, have been extensively incorporated into electrochemical biosensor platforms for heavy metal detection.[21] Aptamer-metal ion interactions typically involve G-quadruplex folding (as in Pb^{2+}-binding aptamers) or structural switching upon metal chelation, transducing binding events into measurable electrochemical signals.[21] Yuan et al.[21] developed an ultrasensitive aptasensor for simultaneous determination of Pb^{2+} and Cd^{2+} in fruit and vegetable samples, achieving LODs of 0.001 µg/L, representing a thousandfold improvement over conventional DPASV on bare electrodes. Screen-printed electrodes (SPEs) have facilitated miniaturisation of aptasensor platforms, enabling disposable, single-use formats compatible with point-of-care environmental testing.[10]

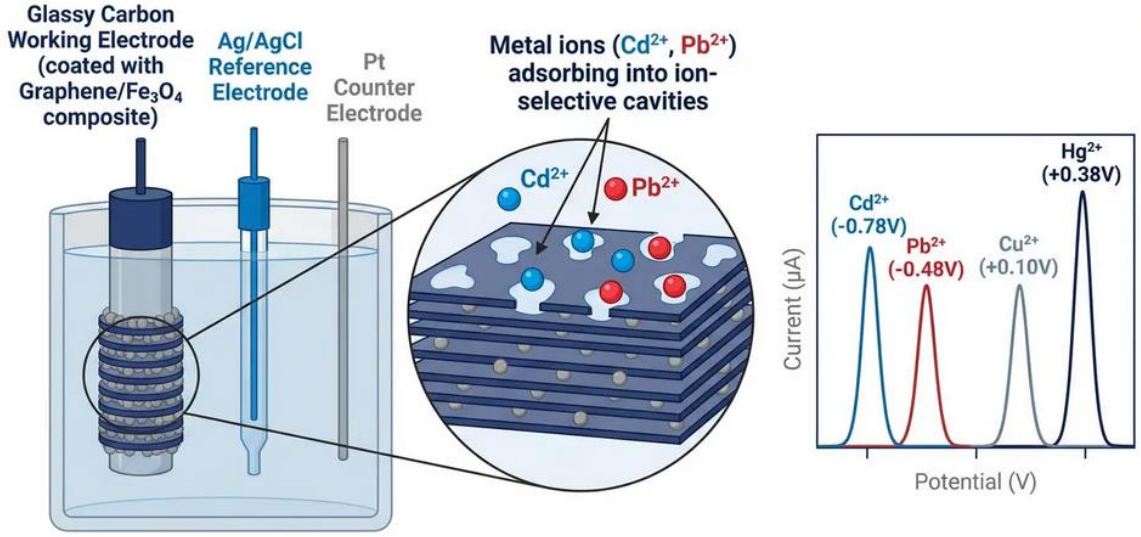

Figure 3: Schematic of a nanomaterial-modified electrochemical sensor for simultaneous multi-metal detection in water samples, showing electrode architecture, stripping voltammetry operational principle, and representative voltammogram with peaks for Cd^{2+}, Pb^{2+}, Cu^{2+}, and Hg^{2+}.

Caption: A professional scientific diagram on a white background illustrating an electrochemical heavy metal sensor system: (1) Left panel – cross-section of a three-electrode electrochemical cell showing a working electrode (glassy carbon) coated with layered nanomaterials (graphene/Fe_3O_4 composite, labelled), a silver/silver chloride reference electrode, and a platinum counter electrode, immersed in a water sample; (2) Middle panel – a zoomed inset showing the nanomaterial surface with metal ions (Cd^{2+}, Pb^{2+} in blue and red spheres) adsorbing into ion-selective cavities; (3) Right panel – a square-wave anodic stripping voltammogram (SWASV) graph showing four distinct oxidation peaks labelled Cd^{2+} (−0.78V), Pb^{2+} (−0.48V), Cu^{2+} (+0.10V), and Hg^{2+} (+0.38V) on a Current (µA) vs Potential (V) axes with navy gridlines

Sources: Authors illustration adapted from references.[10,11,12,13]

7. Sample Preparation Strategies

Irrespective of the detection technique employed, rigorous sample preparation is a prerequisite for accurate heavy metal quantification in environmental matrices. Solid matrices (soil, sediment, plant tissue) require complete dissolution of the mineral or organic matrix to render analytes soluble and amenable to solution-phase analysis.[20,25] Microwave-assisted acid digestion (MAD) using HNO_3, HCl, HF, and H_2O_2 mixtures under elevated temperature and pressure is the method of choice, offering shorter digestion times, improved analyte recovery for volatile metals (e.g., Hg, As), and reduced contamination risk compared to conventional open-vessel digestion.[20] Green analytical chemistry principles, evaluated using the AGREEprep metric developed by Wojnowski et al.[20] have prompted adoption of dilute acid microwave digestion and H_2O_2-only digestion protocols that minimise solvent consumption and laboratory waste generation.[25]

Water samples generally require acidification with HNO_3 (pH < 2) for preservation and may need pre-concentration steps (solid-phase extraction, cloud-point extraction, ionic liquid-based dispersive liquid-liquid microextraction) prior to ICP-MS or GFAAS analysis when target concentrations are below instrument detection limits.[9] For speciation analysis, careful preservation at low temperature and pH control are essential to prevent interconversion of metal species (e.g., As(III)/As(V), Cr(III)/Cr(VI)) between sampling and analysis.[8] Biological matrices (blood, urine, plant tissue) require protein precipitation or microwave digestion before elemental analysis, with particular attention to volatile metal containment.

8. Emerging Trends and Future Directions

The convergence of nanotechnology, microfluidics, and machine learning is reshaping the landscape of heavy metal analysis toward miniaturised, automated, and intelligent platforms. The incorporation of nanomaterials including gold nanoparticles, quantum dots, metal-organic frameworks (MOFs), and MXenes into optical and electrochemical sensor designs continues to push detection limits into the sub-ng/L range while improving selectivity.[11,13] Internet of Things (IoT)-connected electrochemical sensors enabling wireless real-time transmission of water quality data represent a frontier application for continuous environmental surveillance, particularly in resource-limited and remote settings.

Chemometric algorithms, including partial least squares regression (PLS), artificial neural networks (ANN), and support vector machines (SVM), have been applied to ICP-OES, LIBS, and XRF spectral datasets to improve quantitative accuracy in complex matrices affected by spectral overlap and matrix effects.[14,16,17] Deep learning models applied to voltametric signals have enabled simultaneous multi-metal quantification with sub-µg/L accuracy.[11] The emergence of green analytical chemistry as a systematic framework, exemplified by the AGREE prep and AGREE metrics, is directing the development of sample preparation and detection protocols toward reduced reagent consumption, lower energy use, and minimised waste.[20,25] Future analytical frameworks are expected to integrate nanotechnology, electrochemical sensing, and IoT systems to enable decentralized and continuous monitoring of heavy metal contamination in environmental matrices.[26] These trends collectively point toward a future where portable, rapid, and environmentally conscious analytical tools are widely accessible even in low-income settings, an imperative for effective environmental governance in Africa and other developing regions.

9. CONCLUSION

This review has demonstrated that modern analytical science offers a rich and expanding toolkit for the sensitive and accurate detection of heavy metals in environmental matrices. While ICP-MS remains the definitive reference method for ultra-trace multi-element analysis, the proliferation of portable XRF, LIBS, and electrochemical sensors is democratising field-based surveillance at reduced cost and complexity. Electrochemical platforms modified with nanomaterials and molecular recognition elements (IIPs, aptamers) have achieved detection limits competitive with or surpassing ICP-based methods for specific analytes in water matrices. Rigorous sample preparation, guided by greenness principles, underpins the integrity of all analytical data regardless of the detection platform.

Future research should prioritise the standardisation of portable sensor platforms against certified reference materials, the development of multiplexed sensing arrays capable of simultaneous determination of all priority heavy metals, and the integration of IoT connectivity for continuous real-time environmental monitoring. Particular attention is warranted to the context of sub-Saharan Africa, where heavy metal pollution from artisanal mining, e-waste recycling, and industrial effluents poses acute public health challenges and where low-cost, robust analytical solutions are most urgently needed. Collaborative interdisciplinary efforts bridging analytical chemistry, environmental science, public health, and data science will be pivotal in translating laboratory innovations into impactful environmental monitoring practice.

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Conflicts of Interest

The authors declare no conflicts of interest.

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REFERENCES

1. Kiran, Bharti R, Sharma R. Effect of heavy metals: an overview. Mater Today Proc. 2022; 51: 880–885. doi: 10.1016/j.matpr.2021.06.278
2. Filipoiu DC, Bungau SG, Endres L, Negru PA, Bungau AF, Pasca B, et al. Characterization of the Toxicological Impact of Heavy Metals on Human Health in Conjunction with Modern Analytical Methods. Toxics. 2022; 10(12): 716. doi: 10.3390/toxics10120716
3. Sarker A, Masud MAA, Deepo DM, Das K, Nandi R, Ansary MWR, et al. Biological and green remediation of heavy metal contaminated water and soils: a state-of-the-art review. Chemosphere. 2023; 332: 138861. doi: 10.1016/j.chemosphere.2023.138861
4. Lafta MH, Afra A, Patra I, Jalil AT, Mohammadi MJ, Baqir Al-Dhalimy AM, et al. Toxic effects due to exposure heavy metals and increased health risk assessment (leukemia). Rev Environ Health. 2024; 39: 351–362. doi: 10.1515/reveh-2022-0227
5. World Health Organization. Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: WHO Press; 2022. ISBN 978-92-4-004506-4.
6. He S, Niu Y, Xing L, Liang Z, Song X, Ding M, et al. Research progress of the detection and analysis methods of heavy metals in plants. Front Plant Sci. 2024; 15: 1310328. doi: 10.3389/fpls.2024.1310328
7. Guo C, Lv L, Liu Y, Ji M, Zang E, Liu Q, et al. Applied Analytical Methods for Detecting Heavy Metals in Medicinal Plants. Crit Rev Anal Chem. 2023; 53(2): 339–359. doi: 10.1080/10408347.2021.1953371
8. Geng C, Dong Z, Zhang T, Yang Z, Xu Z, Liang S, et al. Advances in atmospheric pressure plasma-based optical emission spectrometry for the analysis of heavy metals. Talanta. 2024; 270: 125634. doi: 10.1016/j.talanta.2024.125634
9. Abdallah O, Bashir K. Quantitative determination of heavy metals in water using ICP-MS. Int J Adv Chem Res., 2023; 5(1): 115–116. doi: 10.33545/26646781.2023.v5.i1b.192
10. Rubino A, Queirós R. Electrochemical determination of heavy metal ions applying screen-printed electrodes based sensors: a review on water and environmental samples analysis. Talanta Open. 2023; 7: 100203. doi: 10.1016/j.talo.2023.100203
11. Yu L, Sun L, Zhang Q, Zhou Y, Zhang J, Yang B, et al. Nanomaterials-based ion-imprinted electrochemical sensors for heavy metal ions detection: a review. Biosensors. 2022; 12(12): 1096. doi: 10.3390/bios12121096
12. Sala A, Brisset H, Margaillan A, Mullot JU, Branger C. Electrochemical sensors modified with ion-imprinted polymers for metal ion detection. TrAC Trends Anal Chem. 2022; 148: 116536. doi: 10.1016/j.trac.2022.116536
13. Dinu Iacob A, Bounegru AV, Iticescu C, Georgescu LP, Apetrei C. Electrochemical Detection of Cd2+, Pb2+, Cu2+ and Hg2+ with Sensors Based on Carbonaceous Nanomaterials and Fe3O4 Nanoparticles. Nanomaterials (Basel). 2024; 14(8): 702. doi: 10.3390/nano14080702
14. Yang Z, Ren J, Du M, Zhao Y, Yu K. Enhanced Laser-Induced Breakdown Spectroscopy for Heavy Metal Detection in Agriculture: A Review. Sensors. 2022; 22(15): 5679. doi: 10.3390/s22155679
15. Ma M, Fang L, Zhao N, Ma X. Detection of Cadmium and Lead Heavy Metals in Soil Samples by Portable Laser-Induced Breakdown Spectroscopy. Chemosensors. 2024; 12(3): 40. doi: 10.3390/chemosensors12030040
16. Ren J, Zhao Y, Yu K. LIBS in agriculture: A review focusing on revealing nutritional and toxic elements in soil, water, and crops. Comput Electron Agric. 2022; 197: 106986. doi: 10.1016/j.compag.2022.106986
17. Yang W, Li F, Zhao Y, Lu X, Yang S, Zhu P. Quantitative analysis of heavy metals in soil by X-ray fluorescence with PCA-ANOVA and support vector regression. Anal Methods. 2022; 14(40): 3944–3952. doi: 10.1039/d2ay00593j
18. Qu M, Guang X, Liu H, Zhao Y, Huang B. Additional sampling using in-situ portable X-ray fluorescence (PXRF) for rapid and high-precision investigation of soil heavy metals at a regional scale. Environ Pollut. 2022; 292(Pt A): 118324. doi: 10.1016/j.envpol.2021.118324
19. Tepanosyan G, Harutyunyan N, Sahakyan L. Revealing XRF data quality level, comparability with ICP-ES/ICP-MS soil PTE contents and similarities in PTE-induced health risk. Environ Geochem Health. 2022; 44(6): 1739–1750. doi: 10.1007/s10653-021-01079-7
20. Wojnowski W, Tobiszewski M, Pena-Pereira F, Psillakis E. AGREEprep – Analytical greenness metric for sample preparation. TrAC Trends Anal Chem. 2022; 149: 116553. doi: 10.1016/j.trac.2022.116553
21. Yuan M, Qian S, Cao H, Yu J, Ye T, Wu X, et al. An Ultra-Sensitive Electrochemical Aptasensor for Simultaneous Quantitative Detection of Pb2+ and Cd2+ in Fruit and Vegetable. Food Chem. 2022; 382: 132173. doi: 10.1016/j.foodchem.2022.132173
22. Abdul Halim A, Sulaiman SS, Nordin AN, Bajunaid Hariz H. Systematic review study on application of ion imprinted polymer (IIP) in heavy metals detection. Int J Environ Anal Chem. 2022. doi: 10.1080/03067319.2022.2106426
23. Khan MI, Talukder AI, Haider A. Laser-Induced Breakdown Spectroscopy (LIBS) for trace element

detection: a review. J Spectrosc. 2022; 2022: 3887038. doi: 10.1155/2022/3887038

24. Singh P, Datta M, Ramana GV, Gupta SK, Malik T. Qualitative comparison of elemental concentration in soils and other geomaterials using FP-XRF. PLoS One. 2022; 17(5): e0268268. doi: 10.1371/journal.pone.0268268
25. Cetinkaya A, Kaya SI, Ozkan SA. An overview of the current progress in green analytical chemistry by evaluating recent studies using greenness assessment tools. TrAC Trends Anal Chem. 2023; 168: 117330. doi: 10.1016/j.trac.2023.117330
26. Oladosu M A, Abah M A, Odimgbe E I, Adewale F E, Arthur C, Ajayi A S et al. Smart Electrochemical Sensors and IoT for Monitoring Heavy Metals in Nigerian Water: Review of Advances and Deployment Challenges. Trends in Ecological and Indoor Environmental Engineering. 2026; 4(1): 79–89. https: //doi.org/10.62622/TEIEE.026.4.1.79-89