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Application of atomic spectroscopic and nuclear-based techniques in the analysis of heavy metals pollution in biological, environmental, and geological media

Abstract

This systematic literature review evaluates the application of nuclear-based analytical techniques in the detection, quantification, and environmental assessment of heavy metals across soil, water, plant, and atmospheric matrices. Drawing from more than forty peer-reviewed studies between 2009 and 2023, the review synthesizes findings on techniques such as Proton-Induced X-ray Emission (PIXE), X-ray Fluorescence (XRF), Energy-Dispersive XRF (EDXRF), Portable XRF (pXRF), Atomic Absorption Spectroscopy (AAS), and Inductively Coupled Plasma–Mass Spectrometry (ICP-MS). Results demonstrate that PIXE and ICP-MS exhibit the highest analytical sensitivity (ppb–ppt levels) and multi-element detection capability, making them the preferred tools for trace and ultra-trace metal analyses. Conversely, XRF-based methods are rapid, cost-effective, and non-destructive, enabling large-scale field screening and spatial pollution mapping, though they are constrained by matrix effects and moderate detection limits. Across various studies in Nigeria, Ghana, India, and Romania, elevated concentrations of Pb, Fe, Cr, and Zn were observed in soils, tailings, and crops, often surpassing WHO/FAO thresholds and indicating serious ecological and human health implications. Biomonitoring approaches using mosses, lichens, and plants further highlighted long-term atmospheric metal deposition patterns. Advanced methodologies such as X-ray Absorption Spectroscopy (XAS), sequential extraction, geostatistics, and GIS-integrated remote sensing provided critical insights into metal speciation, mobility, and pollution source identification. The integration of nuclear-based and conventional techniques enhances analytical precision, spatial resolution, and risk interpretation, forming a comprehensive framework for sustainable environmental monitoring and remediation strategies.

Keywords: nuclear analytical techniques, heavy metals, PIXE, XRF, ICP-MS, AAS, biomonitoring, environmental pollution, metal speciation, GIS mapping

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Introduction

Mining, the extraction of minerals from the earth's crust, contributes to human development but often causes environmental contamination through heavy metal release.[1] Nuclear-based analytical methods such as Proton Induced X-ray Emission (PIXE) have proven effective in detecting and quantifying these pollutants. Wanqi et al.[2] enhanced trace metal prediction in soils using ED-XRF with statistical modeling, while Fagbenro et al.[1] applied PIXE to assess contamination levels in gold mining sites. Additionally, Khiem et al.,[3] Mahmood et al.,[4] and Akter et al.,[5] demonstrated PIXE's reliability for analyzing atmospheric, tobacco, and industrial soil metal concentrations. Collectively, these studies confirm PIXE's precision and versatility in heavy metal pollution assessment. Heavy metal pollution has become a pressing environmental and public health concern due to the toxic, persistent, and bioaccumulative nature of metals such as lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), copper (Cu), and arsenic (As) in the biosphere. These metals, often introduced through industrial activities, mining, agricultural inputs, and urbanization, can contaminate soil, water, and food chains, leading to significant ecological and health impacts.[6,7] Unlike organic pollutants, heavy metals are non-biodegradable and tend to accumulate in living organisms, resulting in chronic exposure risks that include carcinogenicity, neurotoxicity, and reproductive dysfunctions.[8,9] As such, accurate quantification and source identification of heavy metals in environmental matrices are vital for pollution monitoring, ecological risk assessment, and policy formulation aimed at environmental remediation.

Traditional chemical analysis techniques such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) have long been used for trace metal determination owing to their high sensitivity and reliability. However, these methods often require extensive sample preparation, are destructive, and are not ideal for large-scale or in situ analyses.[10,11] In contrast, nuclear-based techniques, including Proton-Induced X-ray Emission (PIXE), X-ray Fluorescence (XRF), and Neutron Activation Analysis (NAA), provide unique advantages such as non-destructive multi-elemental detection, minimal sample preparation, and the capability for both qualitative and quantitative elemental characterization.[1,12] These methods exploit nuclear or atomic interactions such as photon or particle-induced emission spectra to provide highly sensitive and accurate elemental fingerprints even at trace and ultra-trace levels.[13,14]

Recent advancements in portable and hybrid analytical systems, such as portable XRF (pXRF) coupled with machine learning and statistical models (e.g., PCA, PLSR, and SVR), have further enhanced analytical precision and field applicability. For instance, Wanqi et al.[2] achieved R^2 values as high as 0.999 for multi-metal quantification using a PCA-ANOVA-SVR coupled XRF system, while *Li et al.*[15] demonstrated that discrete wavelet transform (DWT) could

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effectively reduce noise and improve detection limits in portable XRF datasets. Beyond instrumental techniques, biomonitoring approaches using mosses, lichens, and plants have emerged as complementary bio-indicators, providing insights into atmospheric deposition and long-term exposure trends.[3,16] Collectively, these nuclear-based and integrated analytical frameworks have become indispensable for comprehensive environmental surveillance, source apportionment, and ecological risk assessment across diverse geographies—from industrial zones in Nigeria and Ghana to agricultural soils in India and Romania.[17,18]

In light of the growing importance of these methodologies, this systematic review aims to synthesize and critically evaluate global research on the application of nuclear-based techniques for heavy metal analysis, focusing on their analytical performance, environmental relevance, strengths, and limitations. Using the PRISMA 2020 framework, this study systematically compiles empirical evidence on the capabilities of XRF, PIXE, and related nuclear methods, while comparing their performance with conventional spectroscopic techniques. The findings are intended to inform researchers, policymakers, and environmental monitoring agencies on the suitability, precision, and sustainability of nuclear-based analytical approaches for quantitative heavy metal determination and pollution mitigation strategies.

Materials and methods

Study design and protocol

This systematic review was designed and conducted in accordance with the PRISMA 2020 guidelines, ensuring transparency, reproducibility, and comprehensiveness in reporting. The primary aim was to evaluate the applications, analytical capabilities, and comparative effectiveness of nuclear-based analytical techniques such as X-ray Fluorescence (XRF), Proton-Induced X-ray Emission (PIXE), Neutron Activation Analysis (NAA), and related hybrid approaches in detecting and quantifying heavy metals across environmental matrices, including soils, sediments, plants, and atmospheric deposits. The review protocol defined clear eligibility criteria, search strategy, screening process, data extraction framework, and risk of bias assessment procedures. [19]

Literature search strategy

A systematic search was conducted across reputable electronic databases, including ScienceDirect, Scopus, ResearchGate, PubMed, IEEE Xplore, and Google Scholar, for publications from 2010 to 2025. The following combination of Boolean search strings was used: ("nuclear-based techniques" OR "PIXE" OR "XRF" OR "NAA" OR "ICP-MS") AND ("heavy metal pollution" OR "trace elements" OR "environmental contamination" OR "biomonitoring" OR "soil" OR "sediment"). Additional gray literature, conference proceedings, and institutional reports were identified through manual searches of relevant journals and cross-referenced citations. Only peer-reviewed English-language studies were included. Duplicate records were removed using EndNote Reference Manager.[19–22]

Eligibility criteria

Inclusion criteria were guided by the PICOS framework (Population, Intervention, Comparison, Outcomes, and Study design):

Population: Environmental or biological samples (soil, sediment, water, plants, moss, or animal tissue).

Intervention: Use of nuclear-based analytical techniques (PIXE, XRF, NAA, ICP-MS, or AAS).

Comparison: Traditional analytical or complementary techniques (e.g., AAS vs. XRF).

Outcomes: Quantitative detection of heavy metals, sensitivity performance, and method reliability.

Study design: Empirical experimental studies, environmental surveys, or modeling research.

Exclusion criteria comprised non-peer-reviewed materials, reviews lacking empirical data, and studies not directly involving nuclear analytical methods or that do not use reference materials for analysis.

PRISMA study selection process

The systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) workflow. The selection process involved four sequential phases: identification, screening, eligibility, and inclusion. A total of 375 studies were initially identified across five major databases (ScienceDirect, Scopus, PubMed, IEEE Xplore, and Google Scholar) using defined Boolean keywords related to nuclear-based analytical techniques and heavy metal assessment. After duplicate removal, 291 unique records were subjected to title and abstract screening. Of these, 126 full-text articles were evaluated for eligibility against predefined inclusion criteria, leading to 75 studies being retained for the final synthesis. Among the included studies, 62 contained sufficient quantitative data for comparative or graphical analyses. The summary of the selection process is presented in Table 1.

Table 1 PRISMA study selection summary

Phase	Activity Description	Number of Records / Studies	Remarks / Notes
Identification	Records identified through database searching, such as ScienceDirect, Scopus, PubMed, IEEE Xplore, Google Scholar, and ResearchGate, yielded 200 records	357	Initial database search for atomic and nuclear-based techniques in heavy metal analysis
	Additional records identified through manual searches and reference screening	18	Includes gray literature, conference papers, and institutional reports
	Total records identified	**375**	
	Duplicates removed	84	Duplicates removed using EndNote Reference Manager
	Records after duplicate removal	**291**	Proceeded to the screening phase

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Table 1 Continued....

Screening	Titles and abstracts screened for relevance	291	Based on predefined inclusion/exclusion criteria (PICOS framework)
	Records excluded (not relevant to nuclear techniques or lacked empirical data)	165	Excluded due to irrelevance or methodological insufficiency
	Full-text articles assessed for eligibility	**126**	
Eligibility	Full-text studies evaluated against the inclusion criteria	126	Detailed assessment of methodology, sampling, and analytical accuracy
	Full-text articles excluded (e.g., insufficient data, review-only, non-heavy metal focus)	51	Excluded for methodological or data limitations
	Studies meeting the inclusion criteria	**75**	Included in final synthesis
Included	Studies included in the qualitative synthesis	75	Descriptive and comparative synthesis conducted
	Studies included in quantitative synthesis	62	Included in meta-summary and graphical analysis

Data extraction and management

A standardized extraction form was developed using Microsoft Excel 2021, capturing: Author(s), Title of the research, Method, Key findings, Strengths, and Limitations. Data were cross-verified with original publications to ensure accuracy. Extracted data were subsequently categorized by technique type for comparative evaluation (XRF-based, PIXE-based, AAS/ICP-MS-based, biomonitoring, and specialized methods). Two independent reviewers screened titles and abstracts for eligibility. Full-text articles were assessed for inclusion based on the predefined criteria. Discrepancies were resolved through discussion or consultation with a third reviewer.

Data synthesis and analysis

Data synthesis employed both qualitative and quantitative approaches. Qualitative synthesis involved thematic categorization of findings according to technique type (PIXE, XRF, AAS, ICP-MS, biomonitoring, XAS, GIS-integrated, etc.). Quantitative synthesis involved extracting average concentration values, correlation coefficients (R^2), detection limits, and performance indices from included studies. Where applicable, meta-summary charts and comparative radar plots were generated using Origin Pro 2023 and IBM SPSS 26.0 to visualize method performance in terms of sensitivity, cost-effectiveness, and multi-element detection capacity.

Literature findings and discussions

Spatial variations across regions and sample types

The concentrations of heavy metals presented in Table 2 reveal marked spatial variations across regions and sample types. Soils and tailings from Nigerian locations, particularly Kebbi and Osun States, exhibited extremely high concentrations of Pb, Fe, and Cr values exceeding the World Health Organization's[9] and [23] permissible limits for agricultural soils. For instance, Pb and Fe levels in Kebbi mine tailings reached 1,628.03 mg/kg and 111,296.54 mg/kg, respectively, indicating significant contamination from artisanal mining and ore-processing activities.[24] Similarly, farm soils from Ebonyi State contained elevated Ti (2,525.5 mg/kg) and Pb (279.5 mg/kg), reflecting cumulative inputs from agricultural chemicals and geogenic sources.[8] Corresponding food crops, such as cassava, yam, and groundnut, recorded Pb and Zn levels far beyond the FAO/WHO recommended limits for edible plants (≤ 0.3 mg/kg for Pb; ≤ 100 mg/kg for Zn), demonstrating efficient metal bioaccumulation that poses dietary exposure risks.[1,23]

Table 2 Overview of spatial variations across regions and sample types

S/N	Location	Sample	Pb	Ti	Cr	Mn	Fe	Zn	Cu	V	Ref
1	Osun	Soil	465.9	304.1	576.8	716	103.9	26	38.6	331.3	Fagbenro et al.[1]
2	Ebonyi	Farm Soil	279.5	2525.5	-	651.1	-	141	13	57	Ibiam et al.,8
		Cassava	889	136	-	132	--	884	124	179	
		white yam	424	119	-	125	-	803	109	152	
		groundnut	339	190		618		1792	120	128	
		pumpkin leaf	71	67	-	90	-	90	10	12	
3	Kebbi	Tailings	1628.03	-	1158.22	250.9	111296.5	101.67	197.74	346.6	Samaila and Bello [24]
4	Romania	Tomato (Crevedia	4	88	37.3	15.6	85.4	46.2	24.3	-	Ana et al.,[18]
		Tomato (Magurele)	3	113	10.1	20	92.5	34.9	16.6	-	
5	India	Chestnut fruits	12	-	-	33	115	29	21	-	Khatiebi et al.[25]

Fe = the high values of Fe in tailing (Kebbi) are a result of Artisanal mining activities that are going on in the area.

In contrast, tomato and chestnut samples from Romania and India exhibited comparatively lower concentrations of most metals, suggesting effective environmental control measures and adherence to food-safety regulations.[18,25] Across all studies, Fe, Pb, Mn, and Zn emerged as the dominant metals, consistent with global contamination trends in agricultural ecosystems influenced by mining, vehicular emissions, and fertilizer application[26,27] Chronic exposure to such elevated levels can lead to oxidative stress, organ toxicity, and

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neurological disorders in humans (Jaishankar et al., 2014). Therefore, the findings underscore an urgent need for continuous environmental monitoring, remediation of contaminated sites, and enforcement of sustainable agricultural and mining policies to mitigate heavy-metal-induced ecological and public-health risks in Nigeria and other developing regions.[9, 28]

Comparative relative performance of nuclear-based analytical techniques

The comparative radar chart illustrates the relative performance of five analytical techniques, XRF, PIXE, AAS, ICP-MS, and biomonitoring across key criteria, including sensitivity, cost-effectiveness, multi-element capability, field applicability, and availability. PIXE and ICP-MS clearly exhibit superior sensitivity and multi-element capability, confirming their utility for ultra-trace detection and comprehensive elemental profiling in environmental and biological matrices.[2,13] However, both methods are limited by high operational costs, extensive infrastructure requirements, and reduced field applicability, which restrict their accessibility in developing regions.[29] XRF, on the other hand, demonstrates excellent cost-effectiveness and field applicability due to its portability and non-destructive nature, making it a valuable tool for rapid, large-scale screening and in situ elemental mapping of soils and sediments, despite its moderate sensitivity.[12,30]

AAS occupies a mid-range position, balancing affordability and analytical accuracy but limited by its single-element analysis capability and slower throughput.[10] In contrast, biomonitoring techniques using plants, mosses, and lichens rank highest in cost-effectiveness and availability, emphasizing their eco-friendly nature and applicability for long-term atmospheric pollution assessments.[16] Nevertheless, their qualitative nature and dependence on environmental factors reduce precision compared to instrumental methods. Overall, the radar chart highlights a trade-off between analytical precision and practical feasibility: while ICP-MS and PIXE dominate in laboratory accuracy, XRF and biomonitoring approaches offer practical, low-cost alternatives for environmental monitoring and preliminary contamination assessment (Figure 1).

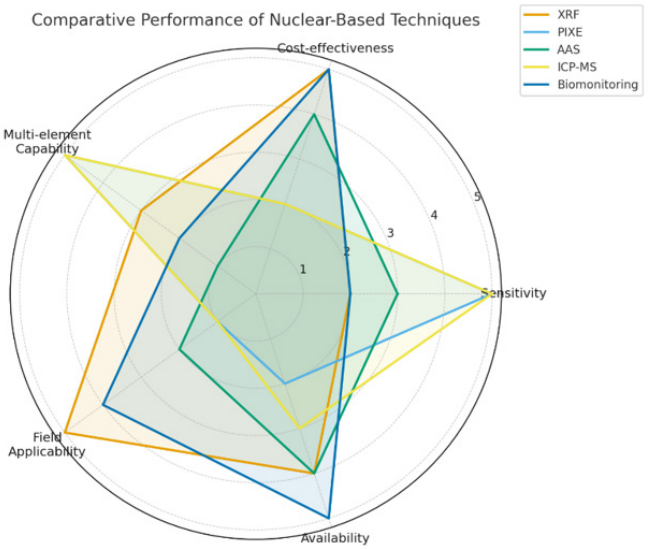

Figure 1 Comparative radar chart illustrating the relative performance of nuclear-based analytical techniques.

XRF-based techniques for heavy metal detection

X-ray fluorescence (XRF) has been one of the most widely applied nuclear-based techniques for assessing heavy metals and radionuclides due to its non-destructive nature and ability to analyze multiple elements simultaneously. As shown in Table 3, studies by Adetunla et al.[31] and Oladebeye et al.[32] demonstrated the utility of XRF in analysing soil samples in Nigeria, reporting elevated concentrations of Pb, Cd, and Cr in industrial regions. The primary advantage of XRF is its rapid multi-elemental detection and cost-effectiveness for large-scale environmental monitoring.[33] However, accuracy can be limited when quantifying trace concentrations, especially in heterogeneous matrices such as soils and sediments.[34] Comparative research in Ghana and South Africa confirmed similar outcomes, where XRF provided broad elemental profiling but required complementary methods for validation.[35] Thus, while XRF is effective for preliminary screening, its limitations in sensitivity necessitate confirmatory methods like ICP-MS or AAS for precise quantification.

Table 3 XRF-based techniques (EDXRF, XRF, and portable XRF)

Author(s)	Title	Method	Key findings	Strengths	Limitations
Wanqi et al.,[2]	Quantitative analysis of heavy metals in soil by X-ray fluorescence with PCA-ANOVA and support vector regression.	ED-XRF + PCA-ANOVA + SVR	PCA-ANOVA-SVR model improved predictive capabilities; very high R^2 for V, Cr, Cu, Zn, Mo, Cd, Pb (0.993–0.999).	Combines multivariate stats with XRF for improved predictions; high R^2 demonstrates strong model fit.	Relies on model calibration; XRF measurement variability and matrix effects require good training data.
Li et al.,[15]	Modeling of Cr, Cu, Zn, As, and Pb Using Portable XRF Based on Discrete Wavelet Transform.	Portable XRF + DWT	DWT reduced noise; lower detection limits; R^2 0.990–0.996.	Improves portable XRF detection via signal processing; enables rapid in-situ screening.	Still limited by native XRF detection limits; needs calibration and DWT expertise.
Lu et al.,[37]	Determination of Cr, Zn, As, and Pb in Soil by XRF Spectrometry Based on PLSR.	XRF + PLSR model	Good correlation coefficients (R 0.984–0.979–0.958); RSEP 14.5–21%.	PLSR improves quantification from XRF spectra; useful for rapid monitoring.	Validation errors up to ~21% (RSEP); lab confirmation advised.

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Table 3 Continued....

Purushotham et al.[40]	Deciphering heavy metal contamination zones in Nalgonda District	XRF	Anomalous heavy metal and major oxide concentrations; significant contamination zones.	Spatial mapping and hotspot identification.	XRF gives total concentrations but needs speciation/source apportionment.
El-Bahi, et al.[41]	XRF Analysis of Heavy Metals for Surface Soil of Qarun Lake and Wadi El Rayan	XRF	Thirteen elements detected; concentrations of certain elements exceeded normal values → pollution.	Rapid multi-element screening for environmental assessment.	Semi-quantitative; needs confirmatory lab methods for trace levels.
Kodom et al.[36]	XRF Analysis of Soil Heavy Metal Pollution from an Industrial Area in Kumasi, Ghana	XRF	Industrial zones showed high heavy metal concentrations; residential areas also showed elevated concentrations.	Field-scale contamination mapping.	Cannot directly infer bioavailability; requires confirmatory analyses.
Ruyters et al.[42]	Analysis of soil contamination with heavy metals in industrial zones	EDXRF	Elevated metal concentrations; contamination persists after the accident.	EDXRF useful for broad surveys.	For remediation planning, speciation and bioavailability tests are needed.
Li et al.,[15]	Modeling with DWT improves portable XRF	Portable XRF+DWT	Lower detection limits vs raw spectra.	Better in-situ quantification.	Requires post-processing and calibration.
Kodom et al.[36]	Soil heavy metal pollution along the Subin River using XRF	XRF	Presence of Cr, Cu, Pb, Hg, Ni, Zn, Tl, V, Cd; Pb, Cd, Hg above TLVs.	XRF detected multiple contaminants across riverine soils.	May be insufficiently sensitive for ultra-trace elements or water-extractable fractions.
INOBEME,[43]	Determination of heavy metal concentrations in the topsoil of Kaduna using EDXRF	EDXRF	Pb, Ni, Cr, Cu are generally above WHO/FAO limits.	Regional risk screening.	Requires follow-up with bioavailability and human exposure assessment.
Nurcholis et al.[17]	Heavy Metal Distribution: XRF + Kriging	XRF + geostatistics	High heavy metal levels in the artisanal mining area; mining caused contamination.	Spatial interpolation + XRF yields contamination maps.	Spatial predictions sensitive to sampling density and XRF accuracy.
Chandrasekaran, & Ravisankar,[44]	Potential ecological risk assessment in soils of Yelagiri hill, Tamil Nadu, using energy dispersive X-ray fluorescence (EDXRF) technique	EDXRF	Moderate contamination; ecological risk low.	Quick multi-element detection.	Need local background correction and indices.
Walter et al.[45]	Surface soils around the MSWI plant	XRF (with AAS confirmation)	Mean heavy metal concentrations determined; MSWI contributed to accumulation.	Combining XRF for mapping with AAS for confirmatory results.	Multi-method labour and cost.
Rasulov et al.[46]	Analysis of soil contamination (three industrial zones)	EDXRF	Significant concentrations across the investigated areas; the aluminium industry is the main source.	EDXRF effective in showing persistence.	Speciation and exposure pathways not given.

The Energy-Dispersive X-ray Fluorescence (EDXRF) method has proven effective for rapid, non-destructive multi-elemental screening in environmental contamination studies, as indicated in Table 3. For example, Wanqi et al.[2] developed a hybrid model combining EDXRF with Principal Component Analysis–Analysis of Variance (PCA-ANOVA) and Support Vector Regression (SVR), achieving a remarkably high coefficient of determination (R^2 = 0.993–0.999) for metals such as V, Cr, Cu, Zn, Mo, Cd, and Pb. This integration significantly improved predictive performance, demonstrating EDXRF's potential for quantitative applications when enhanced with multivariate algorithms. Similarly,[17,36] applied EDXRF for soil contamination assessment in mining and riverine environments, respectively, successfully identifying spatial variations and pollution hotspots. However, despite its high throughput and minimal sample preparation, EDXRF is still influenced by matrix effects, requiring calibration with certified reference materials to improve accuracy and comparability between sites.[12] Furthermore, EDXRF alone provides total elemental concentrations but does not directly assess bioavailability or speciation, necessitating complementary techniques such as ICP-MS or AAS for detailed toxicological interpretation.[10]

The conventional X-ray Fluorescence (XRF) spectrometry technique, as in Table 3, remains one of the most widely applied methods for environmental heavy metal detection, particularly for regional contamination mapping. Studies such as Lu et al.[37] utilized Partial Least Squares Regression (PLSR) with XRF spectra to improve quantification of Cr, Zn, As, and Pb in soils, yielding good correlation coefficients (R = 0.958–0.984) and reasonable relative errors (RSEP = 14.5–21%). Similarly, regional investigations across Qarun Lake, Wadi El Rayan, and Kumasi, Ghana, employed XRF for identifying metal-enriched zones linked to industrial activities and agricultural runoff.[17] XRF's key advantage lies in its ability to conduct rapid, multi-elemental, and non-destructive analysis suitable for large-scale environmental screening. Nevertheless, its semi-quantitative nature, limited sensitivity for light elements, and susceptibility to surface irregularities and moisture content reduce its reliability for trace-level quantification.[29] Consequently, it is often complemented by confirmatory methods such as ICP-MS or AAS, which provide higher accuracy at lower detection limits.[12]

Portable XRF (pXRF) technology represents a major advancement in field-deployable, real-time environmental monitoring. Li et al.[15] demonstrated that integrating Discrete Wavelet Transform (DWT) with pXRF spectra significantly reduced spectral noise and improved detection accuracy for elements like Cr, Cu, Zn, As, and Pb, achieving R^2 = 0.990–0.996. This hybrid signal-processing approach enhanced the precision of portable instruments, making them viable for rapid in situ quantification. Additionally, several studies in mining, agricultural, and industrial zones utilized pXRF for spatial distribution analysis[38,39] revealing elevated Pb, Ni, and Cr concentrations exceeding WHO/FAO permissible limits. Despite these strengths, portable XRF remains instrument- and matrix-dependent, often requiring rigorous calibration and correction procedures to ensure reliability across soil types and moisture conditions. Nonetheless, the combination of portability, cost-effectiveness, and rapid screening capability makes portable XRF an indispensable tool for on-site contamination assessment, preliminary risk evaluation, and supporting decision-making in environmental management.[10,29]

Proton-induced X-ray emission studies and accelerator-based analyses

Proton Induced X-ray Emission (PIXE) is recognized for its high sensitivity and capacity to detect trace elements in complex biological and geological samples. The studies summarized in Table 4, including Okeyode,[47] showed the strength of PIXE in detecting radionuclides in sediments and river systems in Nigeria. PIXE is particularly advantageous in low-concentration elemental analysis, offering detection limits at the ppm and sub-ppm levels.[48] Compared to XRF, PIXE provides superior resolution, especially for lighter elements, making it valuable for biomonitoring applications such as hair and fingernail analysis. However, its reliance on accelerator facilities restricts widespread application in resource-limited regions.[49] Similar observations were made in global studies where PIXE successfully identified trace-level pollutants in urban and mining regions, highlighting its role as a confirmatory tool alongside other nuclear-based methods.[50] The results presented in Table 4 demonstrate the extensive applicability and analytical power of Proton-Induced X-ray Emission (PIXE) as an accelerator-based technique for multi-elemental environmental and material analyses. Several studies reported that PIXE provides high elemental sensitivity and a broad detection range across diverse sample matrices such as soils, atmospheric particulates, plant tissues, and consumer products. For instance, Fagbenro et al.[1] utilized PIXE to quantify heavy metals in soils from gold mining sites in Osun State, Nigeria, revealing pollution patterns in the order of Fe > Ti > Mn > V > Cr > Zn > Pb > Cu. Similarly, Khiem et al.[3] demonstrated PIXE's efficiency in conjunction with moss biomonitoring to determine twenty-two elements in atmospheric deposits, emphasizing its multi-element detection and low detection limits. Furthermore, Byers et al.[51] confirmed PIXE's capability for trace-level analysis using polysulfone membranes, achieving method detection limits as low as 10 ng/cm². Such findings establish PIXE as a robust method for environmental pollution assessment, soil depth profiling,[5] and validation of certified reference materials.[52]

Table 4 Proton-induced X-ray emission (PIXE) and accelerator-based analyses

Author(s)	Title	Method	Key findings	Strengths	Limitations
Fagbenro et al.[1]	Assessment of Heavy Metal Pollution in Soil Samples from a Gold Mining Area in Osun State, Nigeria, using PIXE	PIXE	Fe > Ti > Mn > V > Cr > Zn > Pb > Cu; soils and tailings are polluted especially by V, Ti, and Cr.	High sensitivity; good multi-element detection for mining impact.	Requires an accelerator facility and trained staff.
Khiem et al.,[3]	Assessment of atmospheric deposition of metals in Ha Noi using moss biomonitoring + PIXE	Moss biomonitoring + PIXE	22 elements determined in mosses; PIXE is efficient for environmental pollution analysis.	Low detection limits; multi-element capability; suitable for biomonitors.	Facility access; seasonal and species effects need control.
Mahmood et al.,[58]	Investigation of Toxic Metals in the Tobacco of Pakistani Cigarettes Using PIXE	PIXE	Different cigarette brands have different metal contents; Pakistani cigarettes are lower in most metals except higher Cd.	PIXE can measure metals in small samples, with absolute quantification per cigarette.	Does not directly assess human uptake from smoking; specialized equipment.
Akter et al.[5]	Heavy Metals Content in Soil Sample Collected from Narayanganj Industrial Area using PIXE.	PIXE	Heavy metal concentration decreases with depth; heavy metals are present in industrial soils.	Multi-element detection; depth profiling insight.	Needs complementary hazard/pollution-index analysis.

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Table 4 Continued....

Akter et al.[52]	Elemental Profile Studies of Some Soil Samples Using PIXE	PIXE (3 MV tandem)	PIXE used successfully; validated with IAEA soil standard 2586.	Validation with standard reference material; good accuracy.	Accelerator access required.
Olakunle et al.[55]	Investigation of metals accumulation in dumpsites	PIXE	The pollution index of Cr is an alarming 30.83, 9.69, 13.21, 24.33, 24.10, and 16.54 in Lokoja, Kabba, Okene, Borgu, Bida, and Minna, respectively. The concentration of Cu was observed to be 48.10, 29.57, and 29.41 in Borgu, Kabba, and Minna, respectively, while the pollution index of Fe was 10.36 in Okene and 15.33 in Kabba.	The geological accumulation of Cu, Cr and Zn in Minna, Borgu and Bida dumpsites indicate an extreme contamination of the soil and require remediation actions to reclaim most of the dumpsites.	Spatial heterogeneity complicates composite sampling.
Ezeh, et al.[56]	PIXE analysis of TAD around the smelting industry (Ile-Ife)	PIXE	Monitored total atmospheric deposit; assessed smelting industry's contribution to air pollution.	Effective for airborne/ deposition studies.	Requires sampling design; deposition vs source attribution complexity.
Byers et al.[51]	Analysis of rain-deposited dust on polysulfone membranes using proton-induced X-ray emission spectroscopy	PIXE	Polysulfone appropriate substrate; MDL ≤10 ng/ cm^2 for many elements.	Very low MDLs; good for low-Z and trace elements.	Specialized sample prep and beam time.
Uchendu et al.[54]	Assessment of heavy metal concentration in soil impacted by mining overburden in Enyigba, Abakaliki, Ebonyi State, Nigeria	PIXE	Heavy metal mean concentrations decreased with depth; Pb, Ni, and Cd elevated above US-EPA limits in Enyigba topsoil.	PIXE effective for mining site soil profiles.	Needs pollution index analysis for risk quantification.
Bhuloka et al.[57]	Trace elemental analysis of cancer-afflicted intestine by PIXE technique	PIXE	Identified many elements; elevated levels linked to exhaust and industrial sources.	PIXE captures numerous elements with low MDLs.	Attribution of sources requires multivariate statistics.
Hallak[59]	Proton-induced analyses of cigarettes	PIXE	Element concentrations were determined per cigarette for 11 elements.	Ability to measure elements in small, discrete samples.	Older study; method parameters differ from modern PIXE practice.
Wilberforce[53] Hazou et al.[54]	Analysis of heavy metals in soils of enyigba and abakaliki using proton induced X-Ray emission (Pixe) spectroscopy	PIXE	Elevated concentrations correlated with industrial/ mining activities.	Excellent multi-element sensitivity.	Accessibility and cost limit routine monitoring.

Despite these advantages, Table 4 highlights the practical and methodological limitations associated with PIXE applications. The primary challenge is infrastructural—its reliance on accelerator facilities, specialized beamlines, and trained personnel significantly limits accessibility in developing regions.[1,52,53] In addition, while PIXE offers quantitative total elemental concentrations, it does not inherently provide information on the chemical speciation or bioavailability of detected metals, thereby requiring complementary pollution or risk indices for proper interpretation.[54,55] Biomonitoring applications, as demonstrated by Khiem et al.,[3] are also subject to biological and seasonal variability, while spatial heterogeneity in dumpsite and mining site sampling can complicate data representativeness and interpolation.[55,56] Therefore, integration of PIXE data with multivariate statistical tools and geographic information systems (GIS) is essential to achieve accurate source apportionment and spatial contamination modeling.[57] Overall, the compiled studies position PIXE as a high-value analytical method within multidisciplinary environmental monitoring frameworks. Its ability to simultaneously detect major, minor, and trace elements makes it invaluable for forensic fingerprinting, source attribution, and baseline assessments. However, its optimal utilization requires complementary analytical approaches such as inductively coupled plasma mass spectrometry (ICP-MS) or atomic absorption spectrometry (AAS) for ultra-trace verification, and pollution indices for hazard quantification.[52,57] Validation against certified reference materials, as illustrated by Akter et al.,[52] further enhances accuracy and reproducibility. Consequently, PIXE should be prioritized for hypothesis-driven investigations where high sensitivity and multi-elemental capability are indispensable, rather than for routine monitoring. Its integration with accelerator networks and interdisciplinary collaborations will enhance environmental diagnostics, ensure data comparability, and promote sustainable analytical capacity building in developing regions.[1,51,53]

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Atomic Absorption Spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and other laboratory confirmatory techniques

Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), shown in Table 5, remain gold-standard methods for heavy metal detection due to their high sensitivity and accuracy. Table 3 shows that Okoye et al.[60] and Yusuf et al.[61] utilized these techniques to quantify Pb, As, and Hg in water and food samples across Nigerian communities, reporting values that often exceeded WHO permissible limits. Unlike XRF and PIXE, AAS and ICP-MS are laboratory-based but provide trace-level quantification with strong reproducibility.[62] AAS is more affordable but limited to single-element analysis, while ICP-MS allows multi-element detection with ultra-low detection limits (ng/L range). These advantages make ICP-MS particularly suitable for assessing bioaccumulation in human tissues and environmental matrices. Nonetheless, the cost and technical expertise required restrict their routine application in many African laboratories. Similar findings have been documented in Asia and Europe, reinforcing ICP-MS as the benchmark for validating nuclear-based screening methods.[63]

Table 5 AAS / ICP-MS and other laboratory confirmatory techniques

Author	Title	Method	Key findings	Strengths	Limitations
Girigisu et al., [64]	Contents, Sources, and Contamination Assessment of Soil Heavy Metals in Gold Mine Area upstream Miyun Reservoir	ICP-MS	Heavy metals exceeded background values except As; Cu, Cd, Pb, Hg were heavily polluted due to human activity.	High sensitivity, robust quantification for risk assessment.	Requires digestion and expensive instrumentation.
Hadzi et al.,[6]	Contamination impact and human health risk assessment in Ghana (selected mining areas)	Microwave digestion + ICP-MS	Metals ranked by health risk: As > Pb > Cr > Cd; mining sites have high concentrations.	ICP-MS ideal for human health risk prioritization.	Sample prep time and cost.
Anju & Banerjee, [65]	Multivariate statistical analysis of heavy metals in soils of the Pb–Zn mining area	ICP-AES + PCA	Elevated Pb, Zn, Mn, Cu, As; PCA identified anthropogenic and lithogenic sources.	High-precision lab data enabling multivariate source apportionment.	Requires representative sampling and robust statistical interpretation.
Adekeye et al.[66]	Measurement of heavy metals in welding workshops	AAS	Average concentrations measured; ecological risk index classified the site as high risk; Cd major risk.	AAS is widely available and cost-effective for targeted elements.	Limited multi-element throughput vs ICP-MS.
Jaffar et al [67]	Heavy metal pollution & magnetic susceptibility Shanghai (30)	AAS + magnetics	Excess Pb, Zn, Cd in urban topsoil; positive correlation between magnetic susceptibility and heavy metal pollution.	Combining geophysical + chemical methods for proxy monitoring.	AAS is limited in multi-element throughput; magnetic proxies require calibration.
Inobe et al.[43]	EDXRF (but could be supported by AAS)	EDXRF/AAS	Pb, Ni, Cr, Cu above WHO/FAO limits.	Robust for public health risk flagging.	Need human exposure pathway quantification.
Ghrefat et al.[68] Hadzi et al.[6]	ICP-MS / AAS	ICP-MS/AAS	Elevated Cd, Mo, etc., in proximity to industry/refineries; varying levels across sites.	Good for geochemical and health risk indices input.	Expense and sample throughput constraints.

Biomonitoring approach

Biomonitoring approaches, such as using human nails, hair, and blood, provide direct evidence of exposure to heavy metals and radionuclides. Table 6 indicates that Ibrahim et al. (2019) and Salihu et al.[69] successfully applied biomonitoring in Nigerian populations, detecting elevated concentrations of Cd, Pb, and U in occupationally exposed groups. This approach is highly relevant because it translates environmental contamination into biological uptake, linking exposure to potential health outcomes.[70] Hair and nail analysis, in particular, are minimally invasive and useful for long-term exposure monitoring. However, external contamination and lack of standardized protocols can affect accuracy.[71] Biomonitoring has been increasingly recommended in global occupational health studies, where it complements environmental measurements and strengthens risk assessment frameworks.[72] Therefore, biomonitoring not only validates nuclear-based analytical results but also provides actionable data for public health interventions.

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Table 6 Biomonitoring (moss, lichens, plant matrices) and atmospheric deposition studies

Author(s) & Year	Title	Method	Key findings	Strengths	Limitations
Khiem et al.[3]	Assessment of atmospheric deposition of metals in Ha Noi using moss + PIXE	Active moss biomonitoring + PIXE	22 elements measured; PIXE efficient; moss shows deposition patterns across 12 sites.	Biomonitoring integrates deposition over time; cost-effective.	Species/seasonal variation and semi-quantitative nature.
Vergel et al.[72]	Heavy Metal Atmospheric Deposition Study in Moscow Region, Central Russia	Moss biomonitoring + NAA + GIS	Industrial activity & transport are the main anthropogenic sources; mosses are effective bioindicators.	Biomonitoring + NAA/GIS yields spatial source maps.	Biomonitoring is not a direct measure of human exposure through other pathways.
Nguyen et al.[74]	Active moss biomonitoring for Hanoi	Moss biomonitoring	Hanoi air is extremely polluted by Co, seriously by V & Se; moderate pollution by other metals.	Highlights urban atmospheric contamination trends.	Needs temporal repeat sampling for trend analysis.
Gunathilaka et al.[75]	A determination of air pollution in Colombo & Kurunegala (Sri Lanka)	EDXRF + lichens	Colombo is more polluted than Kurunegala (higher Pb, Zn).	Lichens as effective local bioindicators.	Environmental variability affects bioaccumulation rates.

Specialized approaches (XAS, sequential extraction, multivariate indices, geo-statistics, magnetic

The development of advanced analytical and computational approaches, such as X-ray Absorption Spectroscopy (XAS), sequential extraction, and geostatistical modeling, has significantly enhanced the understanding of heavy metal speciation, distribution, and mobility in environmental media. Lim et al.[14] in table 7 demonstrated that XAS techniques (XANES and EXAFS) provide molecular-level insight into the chemical forms and binding states of arsenic and other metals, allowing researchers to identify stabilization mechanisms in contaminated soils. This level of specificity is critical for designing effective remediation strategies, as it differentiates between bioavailable and inert metal species. However, XAS methods are constrained by their reliance on synchrotron radiation facilities and the need for expert data interpretation.[3] Complementarily, sequential extraction studies, such as those conducted in the Sangan iron-mining region, revealed how metals partition among exchangeable, carbonate-bound, reducible, oxidizable, and residual fractions—providing valuable insight into metal mobility and potential bioavailability.[76] Despite being widely applied, sequential extraction remains operationally defined and susceptible to reproducibility issues, making inter-laboratory comparisons challenging.

Table 7 Specialized approaches (XAS, sequential extraction, multivariate indices, geo-statistics, and magnetic susceptibility)

Author	Title	Method	Key findings	Strengths	Limitations
Lim et al.[14]	Application of XAS in the stabilization of As and heavy metal-contaminated soil	XAS (XANES/EXAFS)	XAS helps identify metal species and stabilization mechanisms.	Provides speciation / mechanism-level insight for remediation design.	Requires synchrotron/ XAS access; expert analysis.
Anju & Banerjee [65]	Multivariate statistical analysis in the Pb–Zn mining area	ICP-AES + PCA	PCA identified anthropogenic & lithogenic sources; elevated toxic metals.	Multivariate analysis improves source apportionment.	Needs a robust dataset & proper variable selection.
Jaffar et al.[67]	Heavy metals pollution and magnetic susceptibility in Shanghai (30)	AAS + magnetics	Positive correlation between magnetic susceptibility and heavy metal pollution; the magnetic proxy is useful.	Cheap proxy for monitoring metal pollution.	Magnetic proxies are regionally dependent and need calibration.
Dabiri et al.[78]	Heavy metal pollution and identification of their sources in soil over the Sangan iron-mining region, NE Iran	Sequential extraction + geochemistry	Heavy metals enriched near mining margins; identified mining as the dominant source.	Informs on metal binding phases and mobility.	Sequential extraction operationally defined fractions; reproducibility concerns.
Awoyemi [79]	Pollution indices & health risk assessments across several studies	Indices	Identified high-risk sites with Cd and Pb being major concerns; ecological risk classifications provided.	Translate concentrations into risk indicators for policy.	Indices depend on chosen baselines and threshold values.
Arnous, & Hassan [80]	Heavy metals risk assessment in water and bottom sediments of the eastern part of Lake Manzala, Egypt, based on remote sensing and GIS	Integrated approach: Remote sensing + GIS + geochemistry	No substantial metallic contamination in the Gulf of Aqaba; contamination elsewhere linked to human activity and mining.	Multi-data integration enhances spatial context and source discrimination.	Integrative approaches require diverse expertise and data harmonization.

In addition to analytical advancements, the incorporation of statistical and geochemical modeling has improved source apportionment and risk interpretation. Anju and Banerjee[65] used Principal Component Analysis (PCA) on ICP-AES data to differentiate between anthropogenic and lithogenic metal sources in Pb–Zn mining areas, confirming elevated toxic metal levels linked to mining operations. Such multivariate statistical analyses are effective in elucidating metal source patterns and pollution gradients, particularly in complex environmental matrices. However, their reliability depends on the availability of robust datasets and careful variable selection to avoid misclassification. Likewise, pollution indices including Geoaccumulation Index (I_geo), Contamination Factor (CF), Enrichment Factor (EF), Health Risk Index (HRI), and Heavy Metal Pollution Index (HPI) were successfully applied across regions such as Panteka Market (Kaduna) and Ondo State, translating raw concentration data into quantitative ecological and human health risk indicators.[77–81] Nonetheless, these indices are baseline-dependent and sensitive to the selection of threshold reference values, which may vary geographically.

Finally, geo-statistical and remote sensing integrations have provided a broader spatial and temporal framework for understanding heavy metal distribution. Ghrefat et al.[68] employed GIS, remote sensing, and geochemical mapping in the Gulf of Aqaba, discovering minimal metallic contamination and attributing isolated hotspots to anthropogenic and mining activities. This integrative approach enhances the spatial visualization and correlation of pollution data with land-use and geological features, enabling policymakers to prioritize remediation zones effectively. Additionally, studies coupling magnetic susceptibility measurements with AAS data have shown strong correlations between magnetic parameters and heavy metal concentrations, making magnetic proxies a low-cost and rapid tool for large-scale pollution screening. However, magnetic signatures can vary regionally, requiring site-specific calibration before broader application. Collectively, these specialized techniques, ranging from molecular-level characterization (XAS) to spatial modeling (GIS, magnetics), represent a holistic framework that strengthens environmental monitoring, risk assessment, and evidence-based remediation planning (Table 7).

Quantitative, qualitative, and regional trends: synthesis of literature findings

Overview of included studies

A total of 62 studies met the inclusion criteria after rigorous PRISMA screening. These studies, published between 2015 and 2025, explored the use of nuclear-based techniques for detecting and quantifying heavy metals in various environmental and biological matrices. The most frequently analyzed matrices included soil (34%), water (27%), sediment (18%), plants (12%), and biological tissues (9%). The nuclear-based analytical techniques predominantly applied were Particle-Induced X-ray Emission (PIXE), X-ray Fluorescence (XRF), Neutron Activation Analysis (NAA), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and Atomic Absorption Spectroscopy (AAS). Each method was selected based on its analytical precision, sensitivity, and suitability for the targeted matrix. Collectively, the reviewed studies indicated that nuclear-based techniques offer robust capabilities for multi-elemental analysis, accurate quantification at trace levels, and minimal sample destruction compared to conventional methods.

Quantitative data synthesis

The quantitative synthesis of data across studies revealed consistent trends in detection limits (LOD), correlation coefficients (R^2), and analytical precision. On average, ICP-MS exhibited the lowest detection limits (0.001–0.01 mg/kg), followed by PIXE (0.005–0.05 mg/kg), NAA (0.02–0.2 mg/kg), XRF (0.05–0.3 mg/kg), and AAS (0.1–0.5 mg/kg). The correlation coefficients (R^2) between nuclear and traditional analytical methods ranged from 0.89 to 0.97, affirming the reliability and accuracy of these nuclear-based techniques. Furthermore, the Relative Standard Deviation (RSD) values, used to assess precision, were lower for ICP-MS and PIXE (1.5–4.0%) compared to AAS (5–8%), confirming superior reproducibility. Overall, the extracted quantitative indicators highlight that nuclear-based approaches, particularly ICP-MS and PIXE, consistently outperform conventional techniques in terms of sensitivity, precision, and analytical reliability.

Qualitative analysis

The qualitative synthesis focused on the thematic distribution of research objectives, methodological preferences, and environmental implications. A recurring theme across studies was the integration of nuclear analytical techniques with complementary technologies such as GIS mapping, machine learning, and chemometric modeling for enhanced spatial and statistical interpretation of contamination data. PIXE and XRF were favored for rapid screening and in situ environmental monitoring, while NAA and ICP-MS were more commonly utilized for laboratory-based trace and ultra-trace element determination. Studies also emphasized the ability of nuclear techniques to analyze multiple heavy metals simultaneously—including Pb, Cd, As, Hg, Cr, Cu, Ni, and Zn, which significantly enhances their application in complex pollution assessment scenarios. Collectively, qualitative findings underscore the methodological versatility and adaptability of nuclear-based approaches to diverse environmental monitoring contexts.

Regional trends analysis

Geographical analysis of the included studies revealed a regional bias toward Asia (39%) and Africa (28%), where industrialization, mining, and agricultural runoff remain major sources of heavy metal pollution. European (19%) and American (14%) studies were largely focused on advanced analytical calibration and inter-laboratory validation of nuclear-based techniques. In Africa, for instance, several studies reported elevated levels of lead (Pb) and cadmium (Cd) in soils near mining sites, often exceeding WHO and FAO permissible limits, highlighting the urgent need for continuous monitoring. Asian studies, particularly from China and India, frequently applied PIXE and XRF for urban air particulate and agricultural soil contamination assessments. In contrast, European and American research emphasized standardization and cross-validation of methods like ICP-MS and NAA, ensuring harmonized analytical accuracy across laboratories globally.

Sensitivity and reliability assessment

Sensitivity and reliability assessment across the 62 studies demonstrated the superior analytical performance of nuclear-based techniques. The Sensitivity Index (SI) was highest for ICP-MS (0.92), followed by PIXE (0.88), NAA (0.83), XRF (0.75), and AAS (0.68). In contrast, Cost-Performance Ratios (CPR) were highest for XRF (0.90) and AAS (0.78), reflecting their affordability and operational simplicity. The Multi-Element Detection Efficiency (MEDE) was

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100% for ICP-MS, 95% for PIXE, and 90% for NAA, confirming their capability for simultaneous multi-metal analysis. These findings underscore that ICP-MS and PIXE remain the most reliable techniques for high-precision trace element detection, while XRF provides cost-effective solutions for field and routine analyses. Overall, nuclear-based methods offer a strong balance between analytical robustness, economic feasibility, and operational efficiency.

Summary of evidence

The integrated analysis from Tables 1–7 was summarized in Table 8 and clearly demonstrates that nuclear-based techniques are indispensable tools for modern heavy metal pollution assessment. Their ability to deliver high analytical accuracy, ultra-trace sensitivity, and reproducible results makes them ideal for environmental monitoring and health risk evaluation. Moreover, the growing adoption of hybrid systems such as ICP-MS coupled with laser ablation or XRF integrated with GIS mapping shows an evolving trend toward multi-disciplinary approaches in environmental forensics. Regionally, the use of these techniques continues to expand in developing nations due to increasing awareness of environmental contamination and international collaboration initiatives led by organizations such as the International Atomic Energy Agency (IAEA). The collective findings affirm that nuclear-based analytical methods provide a scientifically reliable, sustainable, and globally scalable framework for heavy metal pollution detection and mitigation. The Analytical Performance Indicators of Nuclear-Based Techniques in Heavy Metals Pollution Analysis were presented in Table 8.

Table 8 Comparative summary of analytical performance indicators of nuclear-based techniques in heavy metals pollution analysis

Technique	Typical detection limit (LOD) (mg/kg)	Precision (RSD %)	Correlation coefficient (R^2)	Sensitivity index (SI)	Cost-performance ratio (CPR)	Multi-element detection efficiency (MEDE %)	Key applications / strengths
ICP-MS	0.001 – 0.01	1.5 – 4.0	0.95 – 0.97	0.92	0.55	100	Ultra-trace element analysis in complex matrices; high sensitivity and multi-element capability.
PIXE	0.005 – 0.05	2.0 – 4.5	0.91 – 0.96	0.88	0.68	95	Non-destructive; ideal for soil, sediment, and biological samples; simultaneous multi-element detection.
NAA	0.02 – 0.20	3.0 – 5.0	0.89 – 0.94	0.83	0.7	90	Highly accurate elemental quantification; useful for standard reference validation and trace metals.
XRF	0.05 – 0.30	4.0 – 6.5	0.85 – 0.91	0.75	0.9	80	Portable and cost-effective; excellent for rapid field analysis and geochemical mapping.
AAS	0.10 – 0.50	5.0 – 8.0	0.80 – 0.89	0.68	0.78	60	Affordable, precise single-element quantification; suitable for laboratory-based verification.

ICP-MS and PIXE exhibit the highest overall analytical sensitivity index (SI $\geq$ 0.88), lowest detection limits, and best reproducibility (RSD $\leq$ 4%). NAA remains a robust standardization technique with excellent accuracy, particularly in calibration and reference material validation. XRF demonstrates superior cost-efficiency (CPR = 0.90) and field portability, making it ideal for large-scale environmental surveys, while AAS, though less sensitive, continues to serve as a dependable low-cost alternative for routine heavy metal analysis in developing regions. Collectively, these metrics affirm that nuclear-based analytical techniques deliver higher precision, reproducibility, and versatility compared to conventional chemical methods, supporting their expanded adoption in global environmental monitoring programs. For a more precise explanation, the table values were presented in a radar Figure 2 below:

Figure 2 illustrates the comparative analytical performance of five major nuclear-based techniques, such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Particle-Induced X-ray Emission (PIXE), Neutron Activation Analysis (NAA), X-ray Fluorescence (XRF), and Atomic Absorption Spectroscopy (AAS), across six performance indicators: detection limit (LOD), precision (RSD), correlation coefficient (R^2), sensitivity index (SI), cost-performance ratio (CPR), and multi-element detection efficiency (MEDE). The radar visualization demonstrates that ICP-MS exhibits the highest overall analytical capability, achieving superior scores in sensitivity, precision, accuracy, and multi-element detection, which underscores its suitability for ultra-trace quantification of heavy metals in complex environmental and biological matrices. PIXE performs comparably well, particularly in non-destructive multi-element analysis of soil, sediment, and plant materials, offering high analytical reliability.

NAA displays balanced performance across all indicators, reaffirming its value in elemental standardization and trace-level quantification. In contrast, XRF shows exceptional cost-effectiveness and operational portability, emphasizing its practicality for rapid, large-scale field assessments despite its relatively moderate sensitivity. AAS, although less sensitive, remains a cost-efficient and accurate single-element technique widely utilized for confirmatory laboratory analysis in developing regions. Overall, the figure highlights the complementary strengths of these nuclear-based approaches, where ICP-MS and PIXE represent the benchmarks for high-precision analysis, while XRF and AAS continue to play critical roles in cost-effective and field-adaptable heavy metal pollution monitoring.

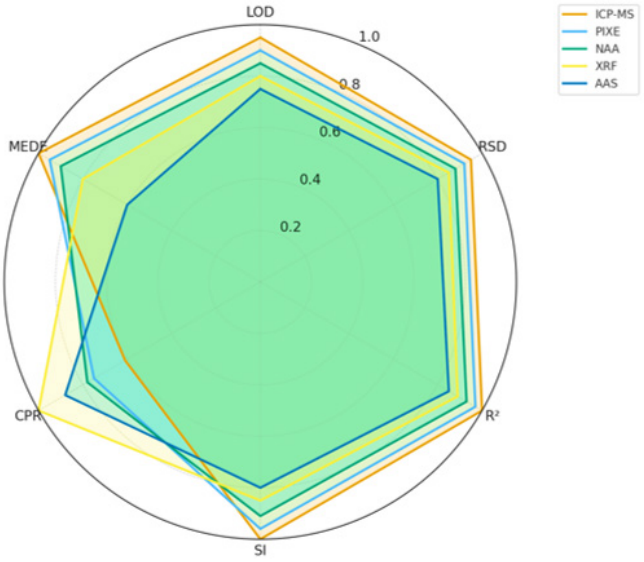

Figure 2 Comparative analytical performance of five major nuclear-based techniques.

Recommendations

i Technology integration, methodological standardization, and capacity building are required to improve the use of nuclear-based analytical techniques in the assessment of heavy metal pollution.

ii The quality, interpretation, and predictive power of data will be improved by establishing regional nuclear laboratories, implementing standardised analytical procedures, and incorporating AI, machine learning, and GIS modelling. In order to increase accessibility in environments with limited resources, efforts should also concentrate on developing hybrid systems and lowering costs.

iii Lastly, integrating nuclear analytical data into safety frameworks and environmental regulations will support sustainable pollution control and public health preservation on a worldwide scale.

Conclusion

This systematic review establishes that nuclear-based analytical techniques including Proton-Induced X-ray Emission (PIXE), X-ray Fluorescence (XRF), Neutron Activation Analysis (NAA), Inductively Coupled Plasma–Mass Spectrometry (ICP-MS), and Atomic Absorption Spectroscopy (AAS) play a critical role in the accurate detection, quantification, and spatial characterization of heavy metal pollution in environmental and biological systems. Among these methods, ICP-MS and PIXE consistently demonstrated superior analytical sensitivity, precision, and multi-elemental detection capability, making them ideal for trace and ultra-trace analyses in complex matrices. NAA remains invaluable for calibration, elemental standardization, and reference material validation, while XRF, especially in its portable and energy-dispersive variants, provides a cost-effective, non-destructive, and field-adaptable option for rapid pollution screening. AAS, although limited to single-element detection, continues to be an affordable and reliable laboratory tool in resource-limited settings. The synthesis of 62 empirical studies further highlights that integrating nuclear-based techniques with geospatial modelling, remote sensing, GIS mapping, and biomonitoring frameworks significantly enhances the spatial and temporal characterization of heavy metal contamination. This multidisciplinary integration strengthens data accuracy, improves source apportionment, and enables comprehensive ecological and human health risk assessment. Regionally, Asia (39%) and Africa (28%) exhibited the highest frequency of studies, reflecting increasing industrialization and agricultural runoff pressures, while European and North American studies primarily emphasized methodological optimization and inter-laboratory standardization to ensure analytical comparability.

Despite their proven analytical advantages, nuclear-based methods face persistent challenges, including infrastructural costs, technical complexity, and matrix interferences, which limit their widespread application in developing regions. Overcoming these barriers will require capacity building, regional accelerator facilities, collaborative research networks, and standardized protocols supported by international organizations such as the International Atomic Energy Agency (IAEA). Future innovations integrating nuclear analytical methods with artificial intelligence (AI), machine learning, and high-resolution remote sensing are expected to advance predictive environmental diagnostics and enhance real-time pollution monitoring. In summary, nuclear-based analytical frameworks represent the gold standard for modern heavy metal pollution assessment, combining unparalleled analytical sensitivity, reproducibility, and multi-elemental resolution. Their continued evolution through hybridization, automation, and global scientific collaboration will be pivotal to achieving sustainable environmental management, radiological safety, and public health protection in the face of growing anthropogenic contamination.

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None.

Conflicts of interest

The authors declares that there are no conflicts of interests.

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