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REVIEW ARTICLE

X-ray applications in metal analysis of soil and plants: Insights from a systematic review

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Abstract

This systematic review explores the development and application of X-ray technologies in the analysis of metal content in soil and plants. X-ray techniques, such as X-ray Fluorescence (XRF), X-Ray Diffraction (XRD), and synchrotron radiation, have emerged as powerful tools for precise, non-destructive, and efficient metal analysis. The review highlights their role in identifying metal contamination in soils, understanding mineral compositions, and studying the bioaccumulation and physiological impacts of metals in plants. Comparative insights reveal the advantages of X-ray methods over traditional approaches, including enhanced sensitivity and rapid analysis, while acknowledging challenges such as cost and accessibility. Future directions emphasize the integration of advanced technologies to expand their applications in environmental and agricultural sciences, underscoring the transformative potential of X-ray techniques in fostering sustainable practices.

Keywords: X-ray analysis, Metal content, Soil analysis, Plant analysis, X-ray Fluorescence (XRF), X-Ray Diffraction (XRD), Synchrotron radiation, Environmental science, Agricultural sustainability, Phytoremediation

Introduction

The analysis of metal content in soil and plants is crucial for understanding environmental health, agricultural productivity, and ecosystem sustainability. Metals play a dual role in these systems: essential micronutrients at low concentrations but potential toxins at higher levels. For example, heavy metals such as Lead (Pb), Cadmium (Cd), and Arsenic (As) can significantly affect soil fertility and pose risks to human health when they enter the food chain (Adriano et al., 2017). Therefore, accurate and efficient methods to analyze and monitor metal content are vital for addressing contamination issues and ensuring food safety (Alengebawy et al., 2021).

Literature Review

Traditional methods, such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), have been widely employed for metal analysis (Aucour et al., 2023). However, these techniques often require extensive sample preparation, destructive processing, and significant time investment, making them less suitable for high-throughput or field-based applications (Smichowski et al., 2018; Wan et al., 2024).

X-ray-based technologies have emerged as transformative tools in metal analysis. Their non-destructive nature, high sensitivity, and ability to provide spatial distribution of elements make them particularly advantageous in soil and plant studies (Jalilehvand et al., 2017). X-Ray Fluorescence (XRF) has been widely used for quantitative analysis of metal concentrations, while X-Ray Diffraction (XRD) provides insights into mineralogical composition. Synchrotron-based X-ray methods further enhance resolution and enable detailed structural analyses at micro and nanoscale levels (Godelitsas et al., 2021; Ghuge et al., 2023).

Methodology

This systematic review followed a structured approach to identify, evaluate, and synthesize relevant studies on the application of X-ray technologies in metal analysis of soil and plants. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were adopted to ensure methodological rigor. A comprehensive search was conducted across multiple scientific databases, including Scopus, Web of Science, and PubMed, using keywords such as "X-ray Fluorescence," "X-ray Diffraction," "metal analysis," "soil," and "plants." Studies published between 2016 and 2023 were included to focus on recent advancements (He S et al., 2024).

Inclusion criteria encompassed peer-reviewed articles that discussed X-ray applications in analyzing metal content in soil and plants, with clear methodologies and reported outcomes. Studies not written in English, those without experimental data, or reviews with limited methodological detail were excluded.

Relevant articles were screened in two phases: first by title and abstract, followed by full-text review. Data were extracted on study objectives, X-ray techniques used, types of metals analyzed, and outcomes reported. A quality assessment was performed to evaluate the reliability and relevance of the included studies. The findings were synthesized thematically, highlighting trends, advancements, and challenges in using X-ray technologies for environmental and agricultural research.

Overview of X-ray technologies

X-ray technologies have become indispensable tools for metal analysis due to their non-destructive nature, high sensitivity, and ability to provide detailed elemental and structural information. The primary techniques used in soil and plant studies include X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), and synchrotron radiation-based methods.

XRF is widely used for the quantitative analysis of metal concentrations in both soil and plant matrices. It works by exciting atoms in the sample with high-energy X-rays, causing them to emit secondary (Fluorescent) X-rays characteristic of the elements present. This technique is highly efficient for detecting trace metals and is particularly valued for its minimal sample preparation requirements (Beckhoff et al., 2020). Portable XRF devices have further expanded its utility in field applications for rapid on-site analysis (Kalnicky & Singhvi, 2019).

XRD provides insights into the crystallographic structure and mineral composition of soil samples. By measuring the diffraction patterns of X-rays interacting with the crystalline lattice, researchers can identify and quantify mineral phases. This method is essential for understanding the speciation and bioavailability of metals in soil (Dyar et al., 2019).

Synchrotron-based X-ray techniques, including X-ray Absorption Spectroscopy (XAS) and micro-XRF, offer unparalleled spatial resolution and sensitivity. These methods enable the detailed investigation of metal speciation, distribution, and interactions at micro and nanoscale levels. Synchrotron radiation has proven particularly effective in studying plant-metal interactions, such as uptake, translocation, and storage in tissues (Manceau et al., 2020).

Recent advancements in X-ray technologies have integrated machine learning and artificial intelligence to enhance data analysis and interpretation. These innovations are paving the way for more precise, automated, and scalable applications in environmental and agricultural sciences (Hirayama et al., 2021).

Applications in soil analysis

X-ray technologies have proven invaluable in soil analysis, particularly for the detection and characterization of metals. Their non-destructive nature, rapid processing, and ability to analyze complex matrices make them a preferred choice in environmental and agricultural research.

X-Ray Fluorescence (XRF) is widely used for identifying and quantifying metal contamination in soils. This technique efficiently detects heavy metals such as Lead (Pb), Cadmium (Cd), and Arsenic (As) at trace levels, offering critical insights into soil pollution and its potential risks to human health and ecosystems (Marguí et al., 2016). Portable XRF devices enable rapid on-site analysis, making them ideal for large-scale environmental monitoring.

X-Ray Diffraction (XRD) is employed to study soil mineralogy and the speciation of metals. Understanding the crystalline structure of soil minerals helps determine the bioavailability of metals, which is crucial for assessing their mobility and environmental impact. XRD is particularly useful in identifying metal-bearing minerals, such as oxides and sulfides, which influence the fate and transport of contaminants (Tian et al., 2017).

X-ray techniques play a significant role in evaluating the effectiveness of soil remediation strategies. For example, synchrotron-based X-ray Absorption Spectroscopy (XAS) has been used to monitor changes in metal speciation following the application of soil amendments, such as biochar or lime. These studies help optimize remediation approaches by providing detailed insights into the chemical forms and stability of metals (Bolan et al., 2018; Chia et al., 2021).

In addition to contamination studies, X-ray technologies are used to analyze essential micronutrients like Iron (Fe), Zinc (Zn), and Copper (Cu) in soils. XRF provides quantitative data on nutrient availability, while XRD aids in understanding the mineral phases that contribute to soil fertility. These analyses support sustainable agricultural practices by ensuring balanced nutrient management (Van der Ent et al., 2021).

X-ray-based soil analyses have been applied in diverse contexts, such as monitoring industrial contamination sites, assessing the impact of mining activities, and studying the effects of agricultural practices on soil health. These applications demonstrate the versatility and importance of X-ray technologies in advancing soil science and environmental protection.

Applications in plant analysis

X-ray technologies have significantly advanced the analysis of metals in plants by enabling detailed investigations of metal uptake, translocation, and accumulation. These non-destructive techniques provide critical insights into plant-metal interactions, contributing to research in agriculture, environmental science, and phytoremediation.

X-Ray Fluorescence (XRF) has been extensively used to study metal uptake and distribution within plant tissues. It allows for the mapping of trace metals, such as Iron (Fe), Zinc (Zn), and Manganese (Mn), in roots, stems, leaves, and seeds. This spatial analysis aids in understanding nutrient dynamics and the physiological roles of metals in plants (Lombi et al., 2011). Portable XRF devices further facilitate in-field monitoring of metal concentrations in crops.

Synchrotron-based X-ray Absorption Spectroscopy (XAS) provides detailed information on the chemical speciation of metals within plant tissues. This information is crucial for understanding how toxic metals, such as Cadmium (Cd) and Arsenic (As), affect plant biochemistry and stress responses. Such studies support the development of strategies to mitigate the adverse effects of metal toxicity in agriculture (Smolders et al., 2013).

X-ray technologies are instrumental in evaluating the potential of plants for phytoremediation, a sustainable method for cleaning metal-contaminated environments. Techniques like XRF and XAS help identify hyperaccumulators plants capable of storing high levels of metals and analyze the speciation of accumulated metals, which determines their mobility and bioavailability in the environment (Kopittke et al., 2019).

In agricultural research, X-ray techniques are used to assess the nutrient content of crops and ensure food safety by monitoring the levels of both essential and toxic metals. For instance, XRF is employed to analyze iron and zinc in staple crops to address micronutrient deficiencies in human diets. Simultaneously, it helps detect harmful metals like lead and arsenic, ensuring compliance with safety standards (Paltridge et al., 2012).

X-ray analyses have been applied in diverse contexts, including studying the effects of fertilizers and soil amendments on metal uptake, monitoring metal dynamics in genetically modified crops, and exploring the mechanisms of metal tolerance in plants. These applications underscore the versatility and importance of X-ray technologies in advancing plant science and sustainable agriculture.

Comparative analysis

Metal analysis techniques in soil and plant studies vary in their sensitivity, cost, speed, sample preparation requirements, and portability. This section provides a comparative analysis of X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), synchrotron radiation-based methods, and traditional approaches like Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Atomic Absorption Spectroscopy (AAS).

Sensitivity

XRF and synchrotron methods demonstrate high sensitivity, particularly for detecting trace metals. Synchrotron techniques, such as X-ray Absorption Spectroscopy (XAS), surpass others in identifying metal speciation at micro and nano levels. ICP-MS is unmatched in sensitivity, capable of detecting metals in parts per trillion, but XRF provides comparable sensitivity for routine field use.

Cost

Cost is a significant factor when choosing an analytical technique. Traditional methods like AAS and ICP-MS involve lower instrument costs compared to synchrotron setups, which require dedicated facilities. However, XRF offers a balance, with moderate costs and portable options that reduce operational expenses in field applications.

Speed

XRF stands out for rapid analysis, especially when using portable devices, enabling immediate results in field conditions. Synchrotron methods, while detailed, require longer data acquisition and processing times. Traditional techniques, such as ICP-MS and AAS, typically involve extensive sample preparation, which increases turnaround time.

Sample preparation

Non-destructive techniques like XRF and synchrotron-based methods require minimal sample preparation, preserving the integrity of samples. In contrast, AAS and ICP-MS often necessitate chemical digestion, which can alter the sample composition and require additional safety measures.

Portability

Portability is a distinct advantage of XRF, particularly with advancements in handheld devices. This feature allows for on-site analysis, making XRF ideal for environmental monitoring and agricultural assessments. Traditional methods like ICP-MS and AAS are laboratory-bound due to the size and complexity of their instrumentation. Synchrotron methods, requiring large facilities, are the least portable (Fig. 1).

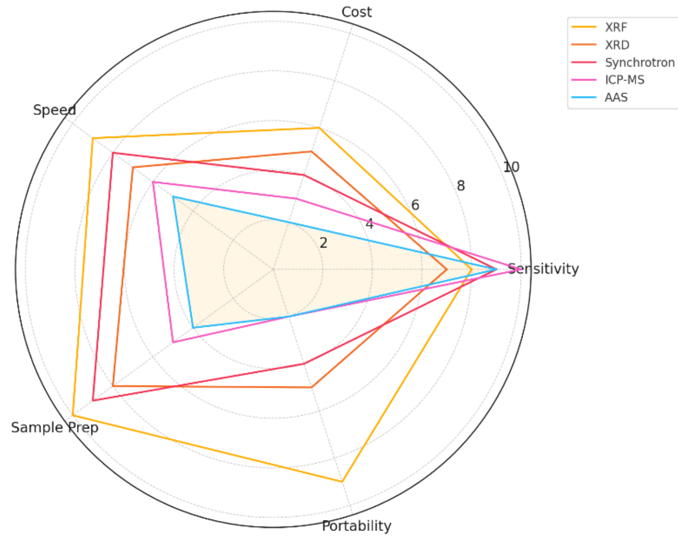

Figure 1. Comparative analysis of metal analysis techniques.

The radar chart above summarizes the comparative features of these techniques. It illustrates the strengths of X-ray technologies, particularly XRF, in aspects like portability, speed, and sample preparation. Synchrotron methods excel in sensitivity and specificity, while traditional techniques like ICP-MS and AAS remain benchmarks for laboratory accuracy.

This analysis highlights that the choice of technique depends on the specific requirements of the study, such as the level of sensitivity, budget, and need for field application. The growing adoption of X-ray technologies underscores their balance of efficiency, accuracy, and practicality, making them invaluable in modern environmental and agricultural research. You can download the radar chart for inclusion in your analysis from the file provided.

Conclusions

This systematic review underscores the transformative role of X-ray technologies in the analysis of metals in soil and plants. Techniques such as X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), and synchrotron radiation have revolutionized environmental and agricultural research by offering precise, non-destructive, and efficient methods for detecting and characterizing metals.

XRF emerges as a versatile tool for rapid on-site assessments, particularly in monitoring metal contamination and evaluating nutrient dynamics. Its portability and ease of use make it highly suitable for field applications, contributing significantly to environmental monitoring and agricultural management. XRD complements XRF by providing detailed insights into the mineralogical composition and speciation of metals, which are crucial for understanding their bioavailability and environmental impact. Synchrotron radiation techniques, while less accessible, provide unparalleled sensitivity and resolution, enabling advanced studies of metal interactions at micro and nanoscale levels.

Comparative analysis highlights the advantages of X-ray methods over traditional techniques, such as ICP-MS and AAS, in terms of speed, minimal sample preparation, and the potential for field deployment. However, challenges remain, including the high cost of advanced X-ray systems and the need for specialized expertise.

Future research should focus on addressing these limitations by developing cost-effective, portable, and user-friendly X-ray technologies. Integrating artificial intelligence and machine learning can further enhance the accuracy and applicability of these methods. Overall, X-ray technologies hold immense potential to advance sustainable practices in soil management, crop production, and environmental remediation, paving the way for innovations in addressing global challenges related to food security and environmental sustainability.

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