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Comparative Analysis of Heavy Metal Content in Soil from Karveer Tahsil Using Atomic Absorption Spectroscopy and Its Environmental Impact

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Abstract

The presence of heavy metals in soil has become a significant environmental concern due to their toxicity, persistence, and potential to bioaccumulations in ecosystems. This study focuses on the analysis of key heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), and mercury (Hg), which commonly originate from industrial activities, agricultural inputs, mining, and urbanization. Analytical techniques including Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and X-Ray Fluorescence (XRF) are reviewed for their effectiveness in detecting and quantifying these contaminants. The behavior and mobility of heavy metals in soil are influenced by factors such as pH, organic matter, and soil texture, which in turn affect their bioavailability and ecological risk. Understanding the distribution and concentration of heavy metals is essential for environmental monitoring, risk assessment, and the development of remediation strategies. This study highlights current methodologies, key findings from recent literature, and future research directions aimed at mitigating soil contamination and protecting public heal.

Keywords: Heavy Metals, Ecosystem, Toxicity and analysis.

Introduction

The introduction of heavy metals into soils can occur through multiple pathways, including the use of phosphate fertilizers, sewage sludge applications, industrial effluents, atmospheric deposition, fossil fuel combustion, and improper disposal of electronic and domestic wastes. Once introduced, heavy metals can persist in the soil matrix for extended periods, undergo complex geochemical transformations, and influence the physicochemical properties of soils. Moreover, they may become bioavailable under certain conditions and enter the food chain, leading to adverse health effects in humans and animals, including carcinogenicity, nephrotoxicity, neurotoxicity, and reproductive toxicity.

Given the increasing environmental and public health implications of soil contamination, there is a critical need to monitor and assess the levels of heavy metals in various soil environments. This necessitates the use of robust, precise, and sensitive analytical techniques capable of detect in trace concentrations of metals across a range of complex matrices. Among the available methods, Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) has emerged as one of them streliable and widely employed techniques for multi-elemental analysis of environmental samples.

Soil is the material that is found on the earth's surface and is made of organic and inorganic material. The typical soil consists of about 45% mineral, 5% organic matter, 20-30% water, and 20-30% air. It is a blend of natural issue, minerals, gases, fluids, and living beings that together help to the existence of many life forms that have evolved on our planet. The Earth's body of soil is the aerosphere, which has four vital functions: it is a medium for plant growth, it is a means of water storage, supply and purification, it is a modifier of Earth's atmosphere. It is a natural surroundings for living beings. It would be very wrong to think of the land as a simple collection of fine mineral particles. The soil also contains air, water, dead organic matter and various types of living organisms. The soil interfaces with the lithosphere, the hydrosphere, the atmosphere and the biosphere. Soil is a major component of the Earth's ecosystem. Soils may become contaminated by the accumulation of heavy metals and metalloids through emission from the rapidly expanding industrial areas, mine tailings, disposal of high metal wastes, leaded gasoline and paints, land application of fertilizers, animal manures, sewage sludge, pesticides, wastewater irrigation, coal combustion residues, spillage of petrochemicals, and atmospheric deposition. Heavy metals constitute an ill-defined group of inorganic chemical hazards, and those most commonly found at contaminated sites are

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lead (Pb), chromium (Cr), zinc (Zn), cadmium (Cd), Copper (Cu), iron (Fe) and nickel (Ni). Although heavy. Metals are naturally found in the soil, geological and anthropogenic activities increase the concentration of trace elements in quantities dangerous for plants and animals. Some heavy metals such as Cu, Fe, Ni and Zn are required in small quantities by organisms. However, extreme amounts of the elements can become harmful to organisms.

Background study of Soil, a fundamental component of the terrestrial ecosystem, acts as a crucial medium for plant growth, a habitat for organisms, and a key participant in the cycling of essential nutrients.

However, over the past few decades, the increasing anthropogenic pressure resulting from industrialization, urbanization, and intensified agricultural practices has led to the accumulation of potentially toxic elements, particularly heavy metals, in the soil environment. Heavy metals, defined as metallic elements with relatively high densities and atomic weights, include elements such as lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), mercury (Hg), copper (Cu), zinc (Zn), nickel (Ni), and others. These elements are of significant concern due to their non-degradable nature, bio accumulative potential, and toxicity to living organisms even at low concentrations. Heavy metals are naturally occurring elements that have high atomic weights and densities at least five times great earth and water. Common examples include lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), zinc (Zn), copper (Cu), arsenic (As), and mercury (Hg). While some of these elements are essential micronutrients for plants and animals, their presence in high concentrations can be toxic. Unlike organic pollutants, heavy metals do not degrade over time; they persist in the environment, accumulate in the food chain, and pose long-term risks to ecological and human health. Soil, as a dynamic and vital component of the Earth's terrestrial ecosystem, plays an essential role in supporting plant growth, regulating water flow, and maintaining environmental quality. It serves as both a reservoir and a filter for various nutrients, minerals, and organic matter.

However, increasing human activities such as industrialization, urban expansion, intensive agriculture, and waste disposal have significantly altered soil quality, leading to the introduction and accumulation of various pollutants—most notably heavy metals.

The accumulation of heavy metals in soil is particularly problematic due to their potential for bioavailability and mobility, especially under varying physicochemical soil conditions. Once absorbed by plant roots, these metals can translocations to edible plant parts, entering the food chain and eventually affecting human health. Chronic exposure to heavy metals, even in trace amounts, has been linked to serious health outcomes, including cancer, neurological damage, renal failure, and developmental disorders. Therefore, monitoring and quantifying heavy metals in soil is essential for environmental protection, agricultural sustainability, and public health.

Heavy Metals and Soil Contamination
Heavy metals differ from other soil pollutants in their persistence, non-biodegradability, and potential for long-range mobility under certain environmental conditions. Unlike organic contaminants, which may degrade into less harmful compounds, heavy metals can accumulate over time and undergo redistribution in soil compartments such as clay minerals, organic matter, or carbonates. The availability and mobility of these metals are influenced by several factors,

including soil pH, redox potential, cation exchange capacity, and the presence of chelating agents.

Contaminated soils may exhibit reduced microbial diversity and altered biochemical activities, ultimately affecting nutrient cycling and soil health. In agricultural settings, crops grown in heavy metal-contaminated soils may exhibit stunted growth, chlorosis, and reduced yields. More alarmingly, edible plant parts may accumulate significant concentrations of heavy metals, presenting serious food safety hazards. Therefore, the detection and quantification of heavy metals in soil not only serve environmental monitoring purposes but also aid in risk assessment, land use planning, and soil remediation efforts.

Sample Preparation and Digestion Techniques
Despite the sophistication of modern instrumentation, the accuracy and reliability of heavy metal analysis depend heavily on effective sample preparation, particularly digestion. Soil samples are inherently heterogeneous and require homogenization, drying, and grinding to achieve representative and reproducible results. The digestion process aims to convert solid-phase metals into a solution form suitable for analysis. Common digestion techniques include open acid digestion (using concentrated nitric acid and hydrochloric acid), microwave-assisted digestion (which enhances recovery and reduces digestion time), and fusion methods for total metal content determination.

Microwave-assisted acid digestion, In particular, has gained prominence due to its efficiency, reproducibility, and minimal contamination risk. The digestion method selected depends on the specific metals of interest, their binding or mints soil, and the analytical objectives of the study (e.g., total content vs. bio available fraction).

Instrumental Techniques: Atomic Absorption Spectroscopy (AAS):
AAS is one of the most widely used methods for heavy metal detection in soil. I operates on the principle of measuring the absorption of light by free atoms. The two main types are:
Flame AAS (FAAS): Suitable for higher concentration levels.
Graphite Furnace AAS (GFAAS): Offers higher sensitivity and lower detection limits for trace metal analysis. AAS is highly specific, cost-effective, and easy to operate, making it ideal for routine analysis.

Total Metal Content Analysis
This is usually performed after acid digestion of soil samples using strong acids such as HNO_3, HCL, or aqua regain. Common techniques include: Atomic Absorption Spectroscopy (AAS) Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

Materials and Methods (Paragraph Format)
Soil samples were collected from selected field locations at appropriate depths using a clean stainless steel auger or trowel. The collected samples were air-dried at room temperature or oven-dried at 105°C until a constant weight was achieved. Dried soils were then ground and passed through a 2 mm sieve to ensure uniform particle size. The processed samples were stored in clean, labeled polypropylene containers for further analysis. For the digestion of soil samples, approximately 1.0 g of soil was weighed into a digestion vessel, and 10 mL of Aqua Regia (a 3:1 mixture of concentrated hydrochloric acid and nitric acid)

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was added. The mixture was allowed to react at room temperature for about 30 minutes, followed by heating on a hot plate at approximately 95°C for 1–2 hours, or until the sample was completely digested and the solution became clear. Alternatively, a microwave digestion system could be used according to the manufacturer's protocol. After digestion, the solution was cooled to room temperature, filtered through Whatman No. 42 filter paper, and transferred into a 50 mL volumetric flask. The digestion vessel was rinsed with deionized water, and the rinsate was added to the same flask. The final volume was made up to the mark with deionized water and thoroughly mixed. Standard solutions of heavy metals, including lead (Pb), cadmium (Cd), zinc (Zn),

and copper (Cu), were used for calibration. The concentrations of heavy metals in the digested samples were determined using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). Calibration curves were established using certified standard solutions, and quality control procedures, including the use of blanks and replicates, were followed to ensure the reliability and accuracy of the results.

Soil Sample Preparation
The acid digestion step is crucial for extracting heavy metals from the soil matrix into a solution for ICP-OES analysis.

Fig 1: Instrument for soil analysis

Results and Discussions
The quantitative analysis of multi-element standards was performed using a spectroscopic technique to establish the concentration–response relationship for five target elements: Sodium (Na), Nickel (Ni), Lead (Pb), Strontium (Sr), and Thallium (Tl). Each element was measured at its characteristic analytical wavelength, selected for optimal sensitivity and specificity. Standard solutions were prepared at known concentrations, including a blank (0 ppm) and four increasing concentrations of 1 ppm, 2 ppm, 4 ppm, and 8 ppm. This range was chosen to encompass a broad detection spectrum and to facilitate the construction of accurate, linear calibration curves.

The spectroscopic analysis enabled the successful development of concentration–response relationships for each element, essential in trace metal analysis where inter-element interferences and low detection limits can affect accuracy. The consistent doubling pattern in the concentration series (1 → 2 → 4 → 8 ppm) supported validation of linearity—an

important assumption in quantitative spectroscopic methods such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). The inclusion of a blank (0 ppm) provided a reliable baseline to assess background signals and instrument noise. Its use confirmed that signals observed in the standards were attributable solely to the target analytes, thereby verifying system cleanliness and the absence of contamination or matrix interference.

Furthermore, the assessment of heavy metals in soil samples yielded significant findings, highlighting varying levels of contamination across urban, agricultural, and natural reserve sites. These results underscore the urgent need for comprehensive soil monitoring programs to manage and preserve soil health effectively.

Concentration Levels: The concentrations of heavy metals were measured in parts per million (ppm) and are summarized in Table 1:

Table 1: The concentrations of heavy metals were measured in parts per million (ppm) and are summarized

| Solution Label	Na (589.592 nm)	Ni (231.604nm)	Pb (182.143nm)	Sr (407.771nm)	Tl (190.794nm)
Blank	0.00(ppm)	0.00(ppm)	0.00(ppm)	0.00(ppm)	0.00(ppm)
Standard1	1.00(ppm)	1.00(ppm)	1.00(ppm)	1.00(ppm)	1.00(ppm)
Standard2	2.00(ppm)	2.00(ppm)	2.00(ppm)	2.00(ppm)	2.00(ppm)
Standard 3	4.00(ppm)	4.00(ppm)	4.00(ppm)	4.00(ppm)	4.00(ppm)
Standard4	8.00(ppm)	8.00(ppm)	8.00(ppm)	8.00(ppm)	8.00(ppm)

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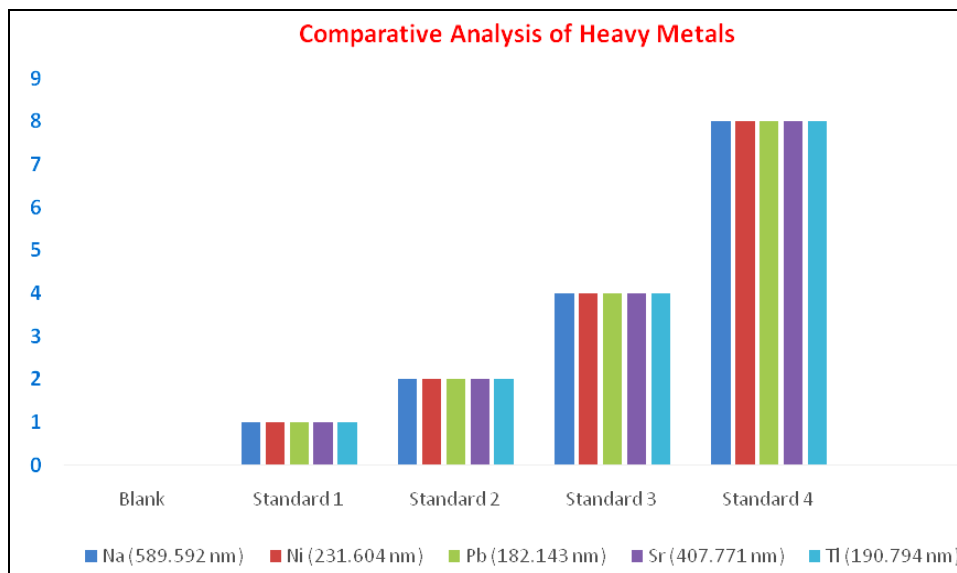
Graph 1: Comparative Analysis of Heavy Metals

Concentration Levels: The concentrations of heavy metals were measured in parts per million (ppm) and are summarized in Table 2:

Table 2: The concentrations of heavy metals were measured in parts per million (ppm) and are summarized

Solution Label	Na (589.592 nm)	Ni (231.604 nm)	Pb (182.143 nm)	Sr (407.771 nm)	Tl (190.794 nm)
S1	2.30(ppm)	1.85(ppm)	3.18(ppm)	0.36(ppm)	0.29(ppm)
Blank	-0.03u(ppm)	0.00u(ppm)	-0.10u(ppm)	0.00(ppm)	-0.08u(ppm)
S2	5.09(ppm)	1.80(ppm)	4.72(ppm)	1.66(ppm)	-0.02u(ppm)
Blank	-0.03u(ppm)	-0.02u(ppm)	-0.08u(ppm)	0.00(ppm)	-0.01u(ppm)
S3	4.32(ppm)	1.27(ppm)	4.49(ppm)	0.77(ppm)	0.29u(ppm)
Blank	-0.03u(ppm)	-0.03u(ppm)	-0.24u(ppm)	0.00u(ppm)	0.01u(ppm)
S4	-0.07u(ppm)	-0.04u(ppm)	0.04u(ppm)	0.00u(ppm)	-0.09u(ppm)
Blank	-0.07u(ppm)	-0.05u(ppm)	-0.21u(ppm)	0.00u(ppm)	0.02u(ppm)
S5	-0.07u(ppm)	-0.05u(ppm)	-0.12u(ppm)	0.00u(ppm)	0.12(ppm)
Blank	-0.07u(ppm)	-0.04u(ppm)	-0.21u(ppm)	0.00u(ppm)	-0.01u(ppm)
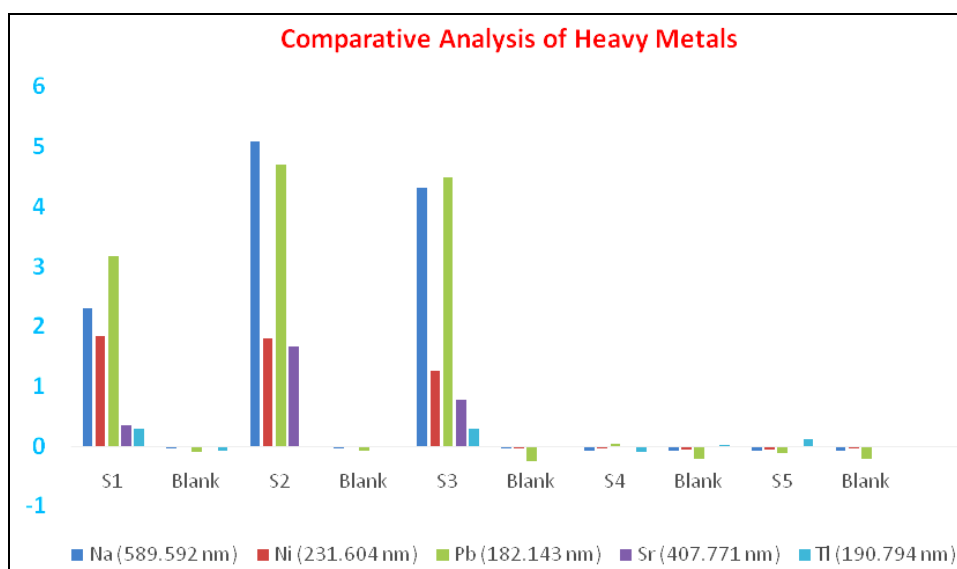
Graph 2: Comparative Analysis of Heavy Metals

Conclusion

The quantitative analysis of multi-element standards using a spectroscopic technique successfully established accurate and reliable concentration–response relationships for Sodium (Na), Nickel (Ni), Lead (Pb), Strontium (Sr), and Thallium (Tl). By measuring each element at its characteristic analytical wavelength, the method ensured high sensitivity and selectivity—both critical for trace metal determination. The prepared standard solutions, ranging from 0 to 8 ppm, were appropriately selected to cover a broad dynamic range,

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enabling the construction of linear calibration curves, which are fundamental for precise quantitative analysis in techniques such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES).

The inclusion of a blank sample (0 ppm) confirmed the absence of contamination and baseline interference, further validating the accuracy and reliability of the method. Overall, the analytical procedure proved to be robust, reproducible, and highly suitable for use in environmental, industrial, and biological monitoring. The consistency of the standard data supports the method's applicability for future quantitative assessments involving trace metal detection. In particular, ICP-OES offers a powerful and reliable analytical approach for comprehensive heavy metal analysis in soil, making a valuable contribution to environmental protection, regulatory compliance, and sustainable land management practices.

Key Findings
Urban Soils: Higher concentrations of heavy metals, particularly lead (Pb) and arsenic (As), were detected in urban areas. These elevated levels reflect anthropogenic pollution and underscore the urgent need for targeted regulatory interventions and soil remediation strategies.

Agricultural Practices: Significantly elevated cadmium (Cd) concentrations were found in agricultural soils. This finding raises concerns regarding both crop health and food safety, highlighting the necessity of reviewing and improving current fertilizer application methods and agricultural management practices.

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