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THE ROLE OF ATOMIC ABSORPTION SPECTROSCOPY IN HEAVY METAL CONTAMINATION AND HUMAN HEALTH RISK ASSESSMENT: A COMPREHENSIVE REVIEW

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ABSTRACT

Heavy metal contamination of the environment having a substantial and growing threat to human health worldwide. Atomic Absorption Spectroscopy (AAS) has seemed as one of the most powerful, reliable, and broadly applied analytical techniques for the quantitative determination of heavy metals in complex environmental, biological, food, and clinical matrices. This review provides a comprehensive overview of AAS principles, instrumentation variants including Flame AAS (FAAS), Cold Vapour AAS (CV-AAS), Graphite Furnace AAS (GFAAS) and Hydride Generation AAS (HG-AAS), their application to heavy metal analysis across multiple samples. The review critically studies the role of AAS in human health risk assessment, covering exposure pathways, toxic mechanisms of import heavy metals including arsenic (As), cadmium (Cd), mercury (Hg), chromium (Cr), nickel (Ni), and lead (Pb), and the application of internationally recognized risk assessment frameworks. Recent methodological advances including high-resolution range source AAS (HR-CS AAS), hyphenated techniques, and automation are discussed. Current limitations and future directions for AAS in environmental health research are also identified.

Keywords: Atomic Absorption Spectroscopy, Heavy metals, Human health risk assessment, Environmental contamination, Trace element analysis, Toxicology

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INTRODUCTION

Heavy metal contamination of the environment has become one of the most tenacious public health concerns of the 21st century. Unlike organic pollutants, heavy metals are non-biodegradable and persist indeterminately in the environment, accumulating in soils, water bodies, sediments, and biological organisms through bioaccumulation and biomagnification procedures **[1]**. Human exposure to heavy metals occurs through multiple pathways — ingestion of contaminated food and water, inhalation of polluted air, and dermal contact with contaminated soils — and chronic exposure, even at low concentrations, is associated with a wide range of serious health outcomes including carcinogenesis, neurotoxicity, nephrotoxicity, hepatotoxicity, reproductive toxicity, and immunosuppression **[2].** The accurate and reliable quantification of heavy metals in environmental and biological matrices is therefore of paramount importance for environmental monitoring, food safety regulation, clinical diagnosis, and human health risk assessment. Among the analytical techniques available for this purpose, Atomic Absorption Spectroscopy (AAS) has occupied a central position since its development by Alan Walsh in 1955 **[3]**. AAS offers a unique combination of high sensitivity, element specificity, relative simplicity of operation, and cost-effectiveness that has made it the technique of choice for routine heavy metal analysis in laboratories worldwide **[4]**. Over the past seven decades, AAS has evolved considerably from its origins as a simple flame-based technique into a family of sophisticated analytical systems capable of detecting heavy metals at the parts-per-billion (ppb) and parts-per-trillion (ppt) levels in complex matrices **[5]**. This evolution has been driven by the need to meet increasingly stringent regulatory limits for heavy metals in drinking water, food, occupational settings, and ambient air, as well as by the demand for more sensitive, automated, and versatile analytical tools for environmental health research **[6]**. This review

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goals to provide a comprehensive and critical synthesis of the role of AAS in the analysis of heavy metals and their implications for human health risk assessment. It covers the fundamental principles and instrumentation variants of AAS, the sources, environmental fate, and toxic mechanisms of priority heavy metals, the application of AAS across key matrices relevant to human exposure assessment, and the methodological frameworks used to translate analytical data into quantitative health risk estimates. Recent technological advances and future directions in AAS-based heavy metal analysis are also discussed.

FUNDAMENTALS OF ATOMIC ABSORPTION SPECTROSCOPY

Basic Principle

The fundamental principle underlying AAS is the absorption of electromagnetic radiation at specific wavelengths by free ground-state atoms in the gaseous phase. Each element possesses a unique electronic configuration that gives rise to characteristic absorption wavelengths, providing the element specificity that distinguishes AAS from many other analytical techniques **[7]**. When a sample is introduced into the instrument and atomized, the free ground-state atoms produced absorb radiation emitted by a light source specific to the element of interest. The reduction in the transmitted light intensity — the absorbance — is measured and related to the analyte concentration as described in the Beer-Lambert Law: **[4]**

$$A = \varepsilon \times c \times l$$

Where A is absorbance, ε is the molar absorption coefficient (L mol^{-1} cm^{-1}), c is the analyte concentration (mol L^{-1}), and l is the path length (cm). Actually, quantification is performed by comparing the absorbance of unknown samples against a calibration curve prepared from standard solutions of known concentration, typically using external calibration, standard addition, or isotope dilution methods **[6]**.

INSTRUMENTATION

Flame AAS (FAAS)

Flame AAS (FAAS) was the first commercially available AAS technique and remains widely used for routine heavy metal analysis due to its simplicity, speed, and low cost **[4]**. In FAAS, the sample solution is nebulized into a pneumatic nebulizer, creating a fine aerosol that is mixed with fuel and oxidant gases and introduced into a burner where atomization occurs. The most commonly used flame types are air-acetylene (for most metals) and nitrous oxide-acetylene (for refractory elements such as aluminium and barium). FAAS typically achieves detection limits in the microgram per litre (µg/L) range, which is sufficient for many environmental and food safety applications but insufficient for ultra-trace analysis **[7]**.

Graphite Furnace AAS (GFAAS)

Graphite Furnace AAS (GFAAS), also known as Electrothermal AAS (ETAAS), was developed by Boris L'vov in the 1960s and represented a major advance in AAS sensitivity **[8]**. In GFAAS, a small volume of sample (typically 5–50 µL) is introduced into a graphite tube and subjected to a programmed sequence of temperature steps — drying, ashing/pyrolysis, and atomization — that progressively removes the sample matrix before rapid atomization of the analyte. GFAAS achieves detection limits 100 to 1000-fold lower than FAAS, typically in the nanogram per litre (ng/L) range, making it suitable for ultra-trace heavy metal analysis in blood, urine, drinking water, and other matrices where regulatory limits are extremely low **[4].**

Cold Vapour AAS (CV-AAS)

Cold Vapour AAS (CV-AAS) is a specialized technique developed exclusively for the determination of mercury (Hg), which is the only metal sufficiently volatile to exist as a monoatomic vapour at room temperature (Welz & Sperling, 1999). In CV-AAS, mercury in the sample is reduced to elemental mercury (Hg^0) using a strong reductant such as stannous chloride ($SnCl_2$) or sodium borohydride ($NaBH_4$), and the resulting mercury vapour is swept by an inert carrier gas through an absorption cell positioned in the optical path of the spectrophotometer. CV-AAS achieves extremely low detection limits for mercury — typically in the sub-nanogram per litre range — and is the reference method for mercury determination in environmental and clinical samples **[9]**.

Hydride Generation AAS (HG-AAS)

Hydride Generation AAS (HG-AAS) is used for the determination of hydride-forming elements including arsenic (As), antimony (Sb), bismuth (Bi), germanium (Ge), lead (Pb), selenium (Se), tellurium (Te), and tin (Sn). In HG-AAS, the analyte is reacted with sodium borohydride in acidic solution to generate a volatile hydride gas, which is swept into a heated quartz atomization cell where decomposition and atomization occur. HG-AAS offers significant advantages over direct FAAS for these elements, including improved sensitivity, reduced matrix interferences, and the ability to determine different oxidation states (speciation analysis) by selective hydride generation conditions **[10]**.

High-Resolution Range Source AAS

High-Resolution Continuum Source AAS (HR-CS AAS) represents the most recent major innovation in AAS instrumentation, replacing element-specific hollow cathode lamps with a single high-intensity xenon short-arc lamp as a continuum radiation source, combined with a high-resolution spectrometer and a charge-coupled device (CCD) detector array. This configuration enables simultaneous measurement at multiple wavelengths,

real-time background correction, multi-element capability, and the ability to monitor molecular absorption for additional analytical information. HR-CS AAS offers significant advantages in terms of instrument versatility, reduced running costs (single lamp for all elements), improved background correction, and the potential for simultaneous determination of multiple elements **[11]**.

PRIORITY HEAVY METALS: SOURCES, ENVIRONMENTAL FATE, AND TOXIC MECHANISMS

Lead (Pb)

Lead is one of the most extensively studied environmental pollutants and a priority heavy metal of global public health concern. Major anthropogenic sources of lead contamination include the historical use of leaded petrol, lead-based paints, lead smelting and mining operations, battery manufacturing, and the use of lead pipes in drinking water distribution systems **[12]**. Lead persists in soil for decades and readily contaminates groundwater through leaching and runoff. Human exposure occurs primarily through ingestion of contaminated food, water, and soil, with children being particularly vulnerable due to higher rates of gastrointestinal absorption and the sensitivity of the developing nervous system **[13]**. Lead exerts its toxic effects through multiple mechanisms, including inhibition of heme biosynthesis enzymes (particularly delta-aminolevulinic acid dehydratase, ALAD), displacement of calcium ions in neuronal signaling pathways, inhibition of N-methyl-D-aspartate (NMDA) receptors, and induction of oxidative stress. Chronic lead exposure — even at blood lead levels previously considered safe — is associated with neurodevelopmental deficits in children, including reduced IQ, impaired attention, and behavioral disorders **[14]**. In adults, lead exposure is linked to hypertension, cardiovascular disease, nephropathy, and reproductive toxicity. The WHO has established that there is no safe level of lead exposure in children **[15]**.

Cadmium (Cd)

Cadmium is a toxic heavy metal classified as a Group 1 human carcer causing agent by the International Agency for Research on Cancer **[16]**. Major sources of environmental cadmium contamination include zinc and lead smelting, phosphate fertilizer application (which naturally contains cadmium impurities), battery manufacturing, electroplating, and cigarette smoking **[17]**. Cadmium accumulates preferentially in agricultural soils and is readily taken up by food crops — particularly cereals, leafy vegetables, and root vegetables — making dietary intake the primary exposure pathway for the non-smoking general population **[18]**. Cadmium is a potent nephrotoxin, accumulating preferentially in the renal cortex where it disrupts proximal tubular function, leading to proteinuria, glucosuria, aminoaciduria, and ultimately renal failure with chronic exposure. It also causes skeletal damage (itai-itai disease), reproductive toxicity, and lung cancer following occupational inhalation exposure. The toxic mechanisms of cadmium include displacement of zinc and calcium in metalloproteins, inhibition of DNA repair enzymes, induction of reactive oxygen species (ROS), and interference with apoptotic pathways **[19]**.

Arsenic (As)

Arsenic is a metalloid classified as a Group 1 human carcinogen and represents one of the most significant environmental health threats globally **[16]** (IARC, 2012). Groundwater arsenic contamination — arising primarily from the natural dissolution of arsenic-bearing minerals in aquifer sediments — affects an estimated 140 million people in over 70 countries, with particularly severe impacts in Bangladesh, India, China, and parts of Latin America and Southeast Asia **[20]**. Additional sources of arsenic exposure include agricultural use of arsenical pesticides, wood preservatives (chromated copper arsenate), smelting operations, and coal combustion. Inorganic arsenic species — arsenite (As^{3+}) and arsenate (As^{5+}) — are considerably more toxic than organic forms, and chronic exposure is associated with a wide spectrum of health effects including skin lesions (hyperkeratosis, melanosis), cancers of the skin, bladder, lung, kidney, and liver, peripheral neuropathy, cardiovascular disease, and diabetes mellitus **[21]**. The toxic mechanisms of arsenic include inhibition of pyruvate dehydrogenase and other thiol-containing enzymes, generation of reactive oxygen and nitrogen species, DNA damage, and epigenetic modifications.

Mercury (Hg)

Mercury exists in multiple chemical forms — elemental mercury (Hg^0), inorganic mercury salts, and organic mercury compounds (particularly methylmercury, MeHg) — each with distinct toxicokinetic and health effects. Major sources of environmental mercury include coal combustion, artisanal and small-scale gold mining (ASGM), chlor-alkali plants, waste incineration, and natural volcanic emissions. Methylmercury is formed from inorganic mercury by anaerobic bacteria in aquatic sediments and undergoes biomagnification through aquatic food chains, reaching the highest concentrations in large predatory fish such as tuna, swordfish, and shark **[22]**. Human exposure to methylmercury occurs predominantly through consumption of contaminated fish and seafood. Methylmercury is a potent neurotoxin that readily crosses the blood-brain barrier and placenta, causing severe neurological damage particularly in the developing fetal brain — manifesting as cerebral palsy, intellectual disability, and sensory impairment, as dramatically illustrated by the Minamata disease outbreak in Japan **[23]**. Elemental

mercury vapour causes pulmonary and neurological toxicity through occupational inhalation exposure, while inorganic mercury salts are nephrotoxic **[24]**.

Chromium (Cr) and Nickel (Ni)

Chromium exists in multiple oxidation states, with trivalent chromium (Cr^{3+}) being an essential trace nutrient and hexavalent chromium (Cr^{6+}) a well-established human carcinogen **[16]**. Sources of hexavalent chromium contamination include chrome plating, leather tanning, stainless steel production, and cement manufacturing. Cr^{6+} is a potent oxidizing agent that generates reactive oxygen species, causes DNA double-strand breaks, and is classified as a Group 1 lung carcinogen following occupational inhalation exposure **[25]**. Nickel is a ubiquitous environmental contaminant arising from nickel mining and refining, stainless steel production, battery manufacturing, and fossil fuel combustion. Nickel compounds are classified as Group 1 human carcinogens (lung and nasal cancers) by IARC, and nickel is the most common cause of allergic contact dermatitis worldwide **[26]**. Toxic mechanisms of nickel include displacement of essential metal ions, inhibition of DNA repair, epigenetic modifications, and activation of hypoxia-inducible factor (HIF-1α) signaling pathways.

APPLICATION OF AAS IN HEAVY METAL ANALYSIS ACROSS KEY MATRICES

Drinking Water and Groundwater

The analysis of heavy metals in drinking water and groundwater is one of the most critical applications of AAS, given the direct implications for human health. Regulatory limits for heavy metals in drinking water are extremely stringent — the WHO guideline values include 10 µg/L for arsenic, 5 µg/L for lead, 3 µg/L for cadmium, and 6 µg/L for mercury — necessitating the high sensitivity of GFAAS or HG-AAS for compliance monitoring **[27].** FAAS is generally insufficient for direct determination of heavy metals at these low levels without preconcentration steps such as solid-phase extraction (SPE) or coprecipitation. Numerous studies have applied AAS to monitor heavy metal contamination in groundwater, particularly in regions affected by geogenic contamination or industrial pollution. Rasool et al. used GFAAS and HG-AAS to characterize arsenic and co-occurring heavy metal contamination in groundwater across Punjab, Pakistan, identifying widespread exceedance of WHO limits and correlating exposure with health outcomes **[28]**. Similarly, AAS-based monitoring programs have been central to characterizing the global groundwater arsenic crisis and informing mitigation strategies **[29].**

Food and Agricultural Products

Food is the primary route of heavy metal exposure for the general population, and AAS is the cornerstone analytical technique for heavy metal monitoring in food safety regulation and risk assessment. Regulatory frameworks including European Union Regulation (EC) No 1881/2006 on contaminants in food, the Codex Alimentarius standards, and national food safety regulations specify maximum levels for heavy metals mainly lead, cadmium, mercury, and arsenic in a wide range of food samples **[30].** AAS has been widely applied to quantify heavy metals in cereals, vegetables, fruits, meat, fish, seafood, milk, and processed foods. GFAAS is mainly valued for the determination of lead and cadmium in food at the extremely low levels mandated by modern regulatory limits, while HG-AAS is a method used as reference for arsenic and mercury concentration in seafood and rice **[18]**. A growing body of literature has applied AAS-based dietary exposure assessment to characterize the contribution of different food groups to total heavy metal intake and to identify high-risk population subgroups including children, pregnant women, and subsistence fishers **[31].**

Soil and Sediment

Soil contamination by heavy metals showing a significant source of human exposure through direct ingestion of soil (particularly in children), inhalation of resuspended dust, consumption of home-grown produce, and leaching to groundwater. AAS typically following acid digestion (aqua regia, nitric acid, or microwave-assisted digestion) is the standard technique for quantifying heavy metals in soil and sediment as part of contaminated land assessment, remediation monitoring, and environmental quality standard compliance **[32]**. Studies using AAS to characterize heavy metal contamination in soils near smelters, mining sites, industrial zones, and heavily trafficked roads have documented high contamination with lead, cadmium, zinc, copper, and arsenic extending over large areas and posing significant health risks to local populations **[33]**. AAS data on soil heavy metal concentrations are routinely used as inputs to human health risk assessment models, including the widely used US EPA Integrated Exposure Uptake Biokinetic (IEUBK) model for childhood lead exposure **[34]**.

Biological and Clinical Matrices

The finding of heavy metals in biological samples blood, urine, hair, tissue and nails is essential for biomonitoring of human exposure and for clinical diagnosis and management of heavy metal poisoning. GFAAS is the reference technique for blood lead determination, which remains the gold standard biomarker of lead exposure in both occupational and environmental settings **[35]**. Blood led levels as low as 1–2 µg/dL well within the detection capability of GFAAS are now recognized as associated with harmful neurodevelopmental effects in children **[14]**.

CV-AAS is the reference method for blood and urinary mercury determination, while HG-AAS or GFAAS is used for urinary arsenic and cadmium,

the primary biomarkers of chronic arsenic and cadmium exposure respectively **[36]**. Biological monitoring data generated by AAS are used in combination with exposure assessment, toxicokinetic modelling, and epidemiological data to establish biological exposure limits, reference values, and guidance values for heavy metals in clinical and occupational health settings.

HUMAN HEALTH RISK ASSESSMENT FRAMEWORK

Overview of Risk Assessment

Human health risk assessment (HHRA) is a systematic, science-based process used to estimate the probability and magnitude of adverse health effects in human populations resulting from exposure to chemical contaminants, including heavy metals. The internationally recognized framework for HHRA, developed by the US Environmental Protection Agency and adopted by regulatory agencies worldwide, comprises four sequential steps: (1) hazard identification, (2) dose-response assessment, (3) exposure assessment, and (4) risk characterization **[37]**.

Exposure Assessment Using AAS Data

AAS-derived concentration data for heavy metals in environmental media (water, soil, food, air) and biological matrices are the primary inputs to the exposure assessment step of HHRA. Exposure assessment involves estimating the magnitude, frequency, duration, and route of contact between a human receptor and a contaminant, and calculating the daily intake or absorbed dose **[37]**. The estimated daily intake (EDI) for dietary exposure is calculated as:

$$EDI = (C \times IR \times EF \times ED) / (BW \times AT)$$

Where heavy metal concentration is C in the food or water (mg/kg or mg/L) determined by AAS, ingestion rate is IR (kg/day or L/day), exposure frequency is EF (days/year), exposure duration is ED (years), body weight is BW (kg), and averaging time is AT (days). AAS concentration data are also used to calculate the Hazard Quotient (HQ) for non-carcinogenic hazard and the Incremental Lifetime Cancer Risk (ILCR) for cadmium, chromium, nickel and arsenic, carcer causing heavy metals such as arsenic, cadmium, chromium, and nickel **[37]**.

Non-Carcinogenic Risk Assessment

Non-carcinogenic risk from heavy metal exposure is characterized using the Hazard Quotient (HQ), calculated by dividing the estimated daily intake (EDI) by the reference dose (RfD) harmful health effects caused by maximum daily intake over a lifetime of exposure **[37]**. Summing the individual HQ values, a Hazard Index (HI) representing the cumulative non-carcinogenic risk from multiple heavy metals is calculated. An HI greater than 1 indicates potential non-carcinogenic risk and warrants further investigation or regulatory action.

Carcinogenic Risk Assessment

For carcinogenic heavy metals including arsenic (skin, bladder, lung cancer), nickel compounds (lung and nasal cancer), cadmium (lung cancer) and hexavalent chromium (lung cancer), cancer risk is estimated as the Incremental Lifetime Cancer Risk (ILCR), calculated by multiplying the daily intake by the cancer slope factor (CSF) or unit risk (UR) for the relevant exposure route **[37]**. An ILCR between 10^{-6} and 10^{-4} is usually considered an acceptable risk range by regulatory agencies, with values exceeding 10^{-4} indicating unacceptable cancer risk demanding regulatory intervention.

RECENT ADVANCES AND FUTURE DIRECTIONS

Significant advances have been made in AAS methodology in recent years, driven by the need for greater sensitivity, selectivity, throughput, and versatility in heavy metal analysis. HR-CS AAS has occurred as a transformative platform offering multi-element capability, real-time background correction, and molecular absorption monitoring within a single instrument **[11]**. Hyphenation of AAS with chromatographic separation techniques, mainly high-performance liquid chromatography (HPLC) and gas chromatography (GC) has extended the capabilities of AAS from total element determination to chemical speciation analysis, enabling the differentiation of toxic inorganic species from less harmful organic forms (e.g., As^{3+} vs. As^{5+} vs. dimethyl-arsenic acid) **[38]**. Automation and flow injection analysis (FIA) coupled to AAS have dramatically increased sample throughput and reproducibility in routine heavy metal monitoring laboratories **[39]**. Miniaturization and the development of portable AAS systems have opened new possibilities for field-based heavy metal monitoring in resource-limited settings and environmental emergency response scenarios **[6]**. Advances in chemometric data analysis including multivariate calibration, machine learning approaches and artificial neural networks are being increasingly applied to AAS spectral data to enhance accuracy in complex matrices and enable multi-element simultaneous determination **[11]**. Despite these advances, AAS faces ongoing competition from multi-element techniques such as ICP-OES and ICP-MS, which offer superior throughput and lower detection limits for many applications. The future role of AAS is likely to be consolidation as the cost-effective, reliable reference method of choice for targeted single or few-element determinations in routine monitoring, occupational health, clinical diagnostics, and food safety compliance, particularly in resource-constrained settings where ICP-based instrumentation is not accessible. Continued innovation in miniaturization, hyphenation, automation and data analysis will confirm that AAS is still an important component of

the analytical toolkit for heavy metal and human health risk assessment well into the future.

CONCLUSION

Atomic Absorption Spectroscopy has played and continues to play a vital and essential role in the detection, quantification, and monitoring of heavy metal contamination across environmental, food, clinical, and occupational matrices. Its exceptional combination of element reliability, specificity, sensitivity, and cost-effectiveness has made it the analytical technique of choice for heavy metal analysis in laboratories worldwide for nearly seven decades. The comprehensive body of AAS-derived data on heavy metal concentrations in environmental and biological matrices forms the practical foundation of human health risk assessment for heavy metals, underpinning regulatory standard-setting, exposure reduction interventions, and epidemiological research that has advanced our understanding of the health consequences of heavy metal contamination. Continued methodological innovation including HR-CS AAS, automation, miniaturization and hyphenated speciation techniques will further spread the capabilities and applications of AAS in environmental health research and risk assessment for decades to come.

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