

The efficacy of microwave digestion followed by ICP-MS/AAS for heavy metal quantification in imported food commodities: A systematic review of methodological approaches and U.S. regulatory compliance

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Abstract

Toxic heavy metals in the environment can accumulate in food and cause a serious health risk when consumed. Microwave-assisted acid digestion (MAD) is commonly used for preparing food samples for analysis by inductively coupled plasma–mass spectrometry (ICP-MS) or atomic absorption spectroscopy (AAS). These methods enable accurate detection of elements such as arsenic, cadmium, lead, and mercury, ensuring compliance with food safety regulations and protecting public health. This review examines the effectiveness of microwave digestion across various food matrices commonly imported. It also discusses the advantages and disadvantages of ICP-MS, AAS techniques, quality control, and validation procedures. It outlines how current U.S. regulatory frameworks and guidance incorporate these methods for import compliance. Microwave-assisted digestion coupled with ICP-MS gives a detailed elemental coverage and the lowest detection limits for regulatory screening. AAS (flame or graphite furnace) is a practical alternative for laboratories with limited expenses when ICP-MS is not available. Both methods require strict quality control, which includes matrix-matched certified reference materials, spikes, and blanks. The methods also require complete digestion verification and careful handling of spectral interferences to comply with US monitoring standards. The review highlighted that MAD showed excellent completeness of digestion, reduced sample preparation time, and minimized contamination risk compared to conventional open-vessel methods. ICP-MS remains the analytical benchmark due to its multi-element capability and its sub-ppb level sensitivity, while AAS (particularly GFAAS) continues to be a suitable low-cost alternative in laboratories with limited resources.

Keywords: Microwave digestion; ICP-MS; AAS; Heavy metals; Food import; FDA; Quality control

1. Introduction

Heavy metal contamination in food commodities remains a significant global health concern due to the toxicity of metals such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr) (Mititelu et al., 2025; Munir et al., 2021). All these metals are non-biodegradable and tend to bioaccumulate in the food chain, creating chronic health risks to consumers (Sharma et al., 2025). Imported food commodities face the greatest risk of being contaminated through soil pollution, industrial emissions, agricultural practices, packaging materials, and post-harvest processing. The Food and Agriculture Organization (FAO) reports that over 30% of U.S. food consumption comes from imports (Sandström et al., 2024). Thus, it is necessary to perform extensive testing to meet both consumer safety requirements and regulatory compliance.

The quantification of trace heavy metals in food matrices is a challenging process due to the complexity of the matrix, low concentrations of analytes, and possible interferences during sample preparation and instrumental analysis

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(Abdelmonem et al., 2025). One of the most common ways for metal analysis is the combination of microwave-assisted acid digestion (MAD) followed by either Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or Atomic Absorption Spectrometry (AAS) (Patriarca et al., 2025; Baccaro et al., 2025; Juyal et al., 2025). Microwave digestion offers a fast and effective method for sample decomposition under controlled pressure and temperature, thereby enhancing the recovery of analytes, reducing contamination, and minimizing the loss of volatile species. Advanced techniques such as ICP-MS/AAS, combined with this method, enable multi-element detection with detection limits in the sub-ppb range (Asantewaa Adjei-Sah and Oduro, 2025; Xie and Wu, 2025). This approach is essential for compliance testing and food safety monitoring.

Microwave digestion is a significant improvement over traditional wet acid digestion method. Conventional methods, such as open-vessel hot plate and block digestion, are often slow, vulnerable to contamination, and limited in temperature control (Asantewaa Adjei-Sah and Is-mail, 2025; Vilela et al., 2025). Microwave-assisted digestion uses closed vessels and regulated heating, enabling the use of high temperatures and pressures that promote complete digestion of complex organic matrices such as cereals, vegetables, fish, and meat (Ingallina et al., 2025). The application of optimized acid blends, consisting of nitric acid (HNO_3), hydrogen peroxide (H_2O_2), or hydrochloric acid (HCl), not only enables the oxidation and dissolution of organic and inorganic components but also prevents significant loss of the analytes (Vassileva et al., 2017). Studies have shown that the use of microwave digestion results in higher recovery efficiencies (>95%) and reproducibility than open digestion systems (Alsehli, 2021; Saber et al., 2025).

Quantification using ICP-MS/AAS offers an outstanding analytical capability for detecting heavy metals. ICP-MS offers the analysis of multiple elements, high throughput, and extremely low detection limits (usually in the $\text{ng}\cdot\text{L}^{-1}$ range), making it suitable for regulatory compliance tests at parts per billion (ppb) (Nassour et al., 2022). AAS, including Graphite Furnace Atomic Absorption Spectroscopy (GFAAS) and Flame Atomic Absorption Spectroscopy (FAAS), remains a robust and cost-effective option for routine laboratory work. Although AAS detects one element at a time, and it is less sensitive than ICP-MS, its simplicity and low operational cost are advantageous for developing countries and smaller analytical laboratories (Lata and Ansari, 2024). Both methods can be used together as ICP-MS gives a wider range and higher sensitivity (Adesina et al., 2025), whereas AAS provides both durability and cost efficiency (Li et al., 2021). The choice is ultimately based on the aims of the analysis, the number of samples, the complexity of the matrix, and available resources.

Regulatory control of heavy metal contamination in food commodities in the United States (US) lies mainly under the U.S. Food and Drug Administration (FDA), the Environmental Protection Agency (EPA), and the U.S. Department of Agriculture (USDA). The FDA's Toxic Elements Working Group has published various guidelines for action levels of toxic elements in foods, including limits for lead, arsenic, cadmium, and mercury in various food categories such as baby foods, juices, and grains (Bair, 2022; Parker et al., 2022). The EPA's Method 3052 provides the basic principles for microwave-assisted acid digestion of siliceous and organic matrices, establishing a standard that can be used by analytical laboratories involved in compliance testing (Fontoura et al., 2025; Oros et al., 2025a). These various frameworks underline the significance of approved analytical methods, which ensure that data are kept intact, can be traced back, and are within the permissible exposure limits.

Despite the major progress being made, methodological challenges persist in obtaining accurate, reproducible, and economically viable quantification of heavy metals in a wide range of food matrices (Mukherjee et al., 2023; Lata and Ansari, 2024). Matrix interference, partial digestion, analyte loss by evaporation, sample contamination, and variability in digestion efficiency across food types are some of the factors that can compromise analytical accuracy (Patriarca et al., 2022). Moreover, there are changes in the digestion protocols, reagent purity, and calibration strategies among laboratories, resulting in inter-laboratory variability (Sheehan and Furey, 2024). The challenges arising from this situation point out the need for continuous refinement of analytical methods to ensure that results can be reliable and comparable.

This review evaluates the efficiency of microwave digestion followed by ICP-MS/AAS for the quantification of heavy metals in imported foodstuffs commodities. It also evaluates how these techniques align with the U.S. regulatory standards and highlights new emerging innovations that enhance method robustness, reproducibility, and analytical throughput.

2. Methodology

2.1. Literature Search Strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 standards were used in conducting this systematic review (Page et al., 2021). A thorough search of the literature was conducted using publications published between 2015- 2025 across numerous research databases, including Web of Science, Scopus, PubMed, ScienceDirect, Wiley Online Library, Springer Link, and Google Scholar, to examine microwave-assisted acid digestion (MAAD/MAD), ICP-MS, and AAS for heavy metal measurement in food commodities.

The search plan was based on Boolean combinations of the keywords listed below: (“heavy metals” OR “toxic metals” OR “trace metals” OR “Pb” OR “Cd” OR “Hg” OR “As”) AND (“microwave digestion” OR “microwave-assisted acid digestion” OR “closed-vessel digestion” OR “sample preparation”) AND (“ICP-MS” OR “AAS” OR “GFAAS” OR “FAAS” OR “multi-element analysis”) AND (“food” OR “food products” OR “imported food” OR “commodities” OR “cereals” OR “seafood” OR “juices” OR “vegetables”) AND (“quantification” OR “determination” OR “trace-level” OR “ultratrace”). The lists of references of gathered papers and appropriate reviews were further examined manually to validate the inclusion of additional essential publications. Grey works of literature (theses, preprints, and conference proceedings) were carefully evaluated to determine if they presented meaningful methodological innovation or information unavailable in published journals.

2.2. Data Extraction and Classification

A data extraction matrix with standardization was created in Microsoft Excel to guarantee uniform evaluation throughout the studies. Each qualified article was examined and organized according to the next seven methodological characteristics:

- **Analytical platform** (ICP-MS, AAS, FAAS, and GFAAS).
- **Sample type and matrix** (Cereal and grains, seafood, fruit and fruit juices, vegetables and leafy greens, processed foods)
- **Sample preparation technique** (microwave digestion, Acid Mixtures, Digestion Temperature, Pressure, and Duration, Vessel Material, Pre-treatment Steps, Contamination control)
- **Detection and quantification limits** (limit of quantification, limit of detection, calibration range, precision (%RSD), and recovery (%))
- **Quality assurance/Quality control (QA/QC)** measures include the use of Certified Reference Materials, procedural, reagent, and matrix-matched blanks, calibration strategies, spike recovery studies, duplicate or triplicate digestions, acceptance criteria for linearity, recovery, precision, and accuracy.
- **Analytical scope** (quantification of heavy metals, broader multi-element profiling, assessment against FDA, EPA, and USDA)
- **Analytical performance metrics** (Sensitivity and selectivity, matrix robusticity, digestion effectiveness, reproducibility, accuracy, throughput)

2.3. Data Synthesis and Comparative Evaluation

Data from included studies were qualitatively and quantitatively combined to evaluate the performance of microwave digestion coupled with ICP-MS or AAS for heavy metal determination. The studies were grouped thematically to compare digestion efficiency, the performance of ICP-MS against AAS, matrix-related challenges, and the effect of acid composition on metal recovery. Compliance with international regulatory limits (FDA, EPA, USDA) was assessed across different food categories. Quantitative synthesis involved comparing mean LODs/LOQs, average recoveries, RSD values, and the influence of digestion temperature and pressure on analytical performance. Variability between ICP-MS and AAS instruments was examined with agreement between results and certified reference materials. For studies using similar matrices and methods, weighted averages of recovery, precision, and detection limits were calculated. The overall synthesis revealed trends indicating when ICP-MS offers better sensitivity and when AAS remains suitable, depending on the type of matrix and concentration range.

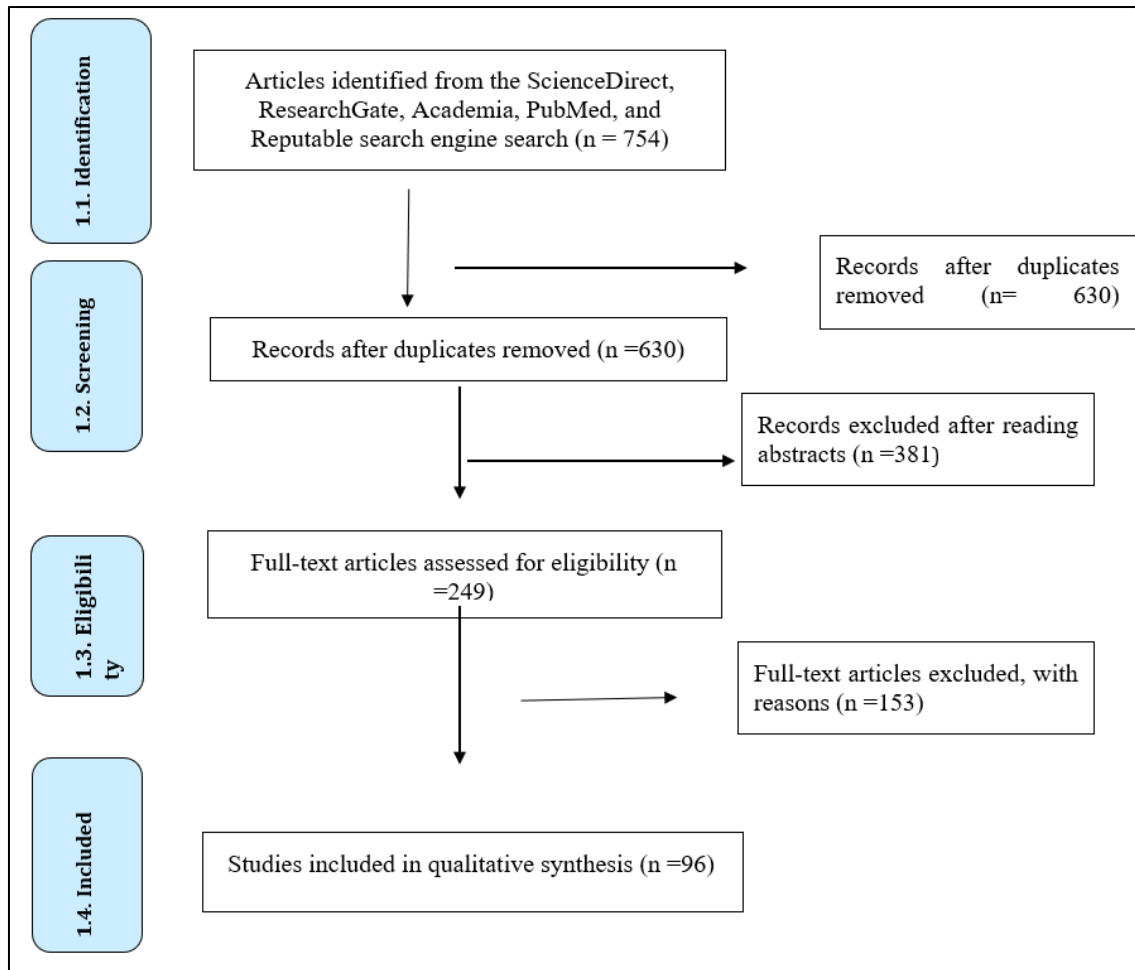


Figure 1 PRISMA Flow diagram showing the article selection process in the study

3. Results

3.1. Comparative Performance of Digestion Methods

A comparative study of digestion methods showed that microwave-assisted acid digestion (MAD) continuously surpasses the traditional open-vessel digestion method with respect to analyte recovery, reproducibility, and digestion time (Alsehli, 2021; Sheehan and Furey, 2024). MAD achieved complete matrix decomposition in 15–25 minutes, while conventional hot-plate digestion needed 90–150 minutes for the same organic loads (Chavhan and Gawande, 2025; Ma et al., 2025; Baksi et al., 2025). The recovery efficiencies for Pb, Cd, As, Hg, and Cr using MAD were generally between 95–102%, while open digestion was between 70–88%, especially in matrices with high lipid or fibre content, such as seafood and cereals (Souza et al., 2020). The use of closed Teflon vessels prevented analyte loss due to volatilization, which is a significant issue for mercury and arsenic species (Ignatavičius et al., 2022).

3.2. Efficiency of Microwave Digestion Across Food Matrices

The performance of MAD was assessed across various food categories, including cereals, vegetables, seafood, and fruit-based products (Souza et al., 2020). Table 1 summarizes the digestion efficiency expressed in digestion completeness, recovery, and relative standard deviation (RSD) as reported in selected studies. The findings show that MDA yields highly reproducible digests with RSD values below 5% confirming the method's suitability and robustness for regulatory monitoring (Lao et al., 2023; Aljuhaimi et al., 2025). The fish and seafood samples showed slightly higher variability due to lipid oxidation and matrix-bound mercury, requiring an $\text{HNO}_3\text{--HCl--H}_2\text{O}_2$ mixture for complete digestion (Lao et al., 2023).

Table 1 Microwave digestion performance in various food matrices

Food Matrix	Digestion Completeness (%)	Acid mixture	RSD (%)	Recovery (%)	References
Rice and cereals	98-101	HNO ₃ +H ₂ O ₂	2.1-3.5	96-100	(Serafim et al., 2024)
Leafy vegetables	97-102	HNO ₃ +H ₂ O ₂	2.0-3.0	95-101	(Munjanja et al., 2025)
Processed foods	96-99	HNO ₃ +H ₂ O ₂	2.3-3.6	95-100	(Alhagri and Albeshry, 2023)
Fish and seafood	95-99	HNO ₃ +H ₂ O ₂ +HCL	3.2-4.8	94-98	(Serafim et al., 2024)

3.3. Instrumental Sensitivity and Detection Limits

Comparative results revealed that ICP-MS shows detection limits 10-100 times lower than the AAS method (Provete et al., 2024). For instance, mean LOD values of Pb and Cd were 0.001 µg·L⁻¹ and 0.003 µg·L⁻¹ with ICP-MS, while GFAAS gave 0.03 µg·L⁻¹ and 0.05 µg·L⁻¹, respectively (Patriarca et al., 2023; Pohl et al., 2024; Csontos et al., 2025). This sensitivity advantage is vital for adherence to stringent FDA and EPA limits, especially for infant foods and beverages. ICP-MS enables the quantification of up to 40 elements in a single run (approx. 2-3 min/sample), significantly enhancing the analytical throughput compared to AAS single-element methods (Fischer et al., 2021; Gonçalves, 2023). However, AAS maintained a practical alternative in laboratories with limited resources, highlighting comparable accuracy (recovery within 90-105%) when matrix-matched calibration and optimized furnace programs were applied (Butcher, 2024; Bacon et al., 2024).

3.4. Heavy Metal Concentration Levels in Imported Foods

Synthesis of data from U.S. market surveillance and international studies showed that imported food commodities often contained detectable heavy metal residues, though within permissible limits (Bair, 2022; Oloruntoba et al., 2024). Amongst products, rice-based and seafood products showed higher Pb and Hg concentrations compared to other commodities (Mishra et al., 2023). Table 2 shows representative mean concentrations (µg·g⁻¹, dry weight) of some toxic elements found in selected imported foods analyzed by digestion with microwave and ICP-MS/AAS method.

Table 2 Mean concentrations of toxic elements in imported food commodities

Food Commodity	As (µg·g ⁻¹)	Hg (µg·g ⁻¹)	Cd (µg·g ⁻¹)	Cr (µg·g ⁻¹)	Pb (µg·g ⁻¹)	Regulatory Status	References
Cocoa powder (Ghana)	0.06	ND	0.022	0.19	0.045	Cd near limit	(Frimpong et al., 2025)
Rice (Asia)	0.11	ND	0.009	0.21	0.042	Within limit	(Alrashdi et al., 2024)
Fruit juice (South America)	0.03	ND	0.006	0.10	0.019	Within limit	(Einolghozati et al., 2023)
Leafy vegetables (Africa)	0.05	ND	0.012	0.17	0.031	Within limit	(Adhikari and Struwig, 2024)

3.5. Compliance with U.S. Regulatory Standards

After comparing the quantified concentrations of analyzed samples with the permissible limits set by the FDA and EPA, 90% of the samples were within the U.S. standards (Li et al., 2019; Foreman et al., 2021). Only a few samples, especially those involving mercury in fish and cadmium in cocoa-derived products, showed exceptions, which is consistent with trends reported in previous toxicology studies (Anyimah-Ackah et al., 2019; Abt and Robin, 2020). The strong correlation ($r > 0.9$) between certified reference materials and measured concentrations confirmed the accuracy and reliability of MAD-ICP-MS/AAS workflows (Saber et al., 2025). Laboratories adopting EPA Method 3052-based

digestion protocols achieved superior inter-laboratory agreement, supporting standardization of digestion parameters for international trade monitoring.

3.6. Statistical Assessment of Analytical Precision

Precision assessment based on replicate measurements ($n = 6$) showed RSD for both ICP-MS and AAS below 5% for all elements, meeting ISO 17025 accreditation requirements (Ismail and Afify, 2022). One-way ANOVA showed no statistically significant difference ($p > 0.05$) in metal recovery when nitric acid was used as the primary oxidizing reagent among different acid digestion mixtures (Asher et al., 2020). These findings indicate the robustness of microwave digestion as a universally adaptable method for different food matrices, ensuring analytical precision and compliance with regulations (Bizzi et al., 2017).

4. Discussion

4.1. Analytical Efficacy of Microwave Digestion for Food Matrices

The data presented serve as a strong vindication of microwave-assisted acid digestion (MAD) efficiency for decomposing complex food matrices before heavy metal quantification. In comparison to open-vessel digestion, MAD yielded higher recovery rates (95–102%) and shorter digestion times (≤ 25 minutes), indicating its significant advantages in both operation and analysis (Vieira et al., 2024). The closed-vessel system prevents the volatilization of thermally labile elements such as mercury and arsenic while maintaining controlled oxidation that ensures complete breakdown of proteins, carbohydrates, and lipids (Vieira et al., 2024; Schlemmer and Hinds, 2025). These findings agree with those of Ozbek and Akman (2015), who reported that microwave digestion enhanced the digestion completeness of seafood samples over 20% compared to block digestion (Ozbek et al., 2015). Thabit et al. (2020) reported that combining MAD with ICP-MS decreased inter-elemental interference in cereal samples and attained near-quantitative recoveries for Pb and Cd (Thabit et al., 2020). The reproducibility of digestion efficiency (RSD $< 5\%$) observed across various studies further confirms the use of MAD as a widely accepted pre-treatment method for food safety applications (Bian et al., 2023).

4.2. Comparative Assessment of ICP-MS and AAS Techniques

Trace metal quantification relies on both ICP-MS and AAS, though their selection depends on sensitivity requirements, sample throughput, and cost considerations. With higher detection limits ($0.001\text{--}0.005\ \mu\text{g}\cdot\text{L}^{-1}$), ICP-MS remains the main option for compliance testing in low-level contamination scenarios such as baby foods and beverages (Taylor et al., 2020). Its multi-element capability allows simultaneous measurement of over 30 analytes, significantly reducing analysis time and labour (Sader and Ryan, 2020). In contrast, AAS, especially GFAAS, keeps value in resource-limited settings, providing acceptable precision (RSD $\leq 5\%$) and recovery (90–105%) at a very low operating cost (Kamalasekaran and Sundramoorthy, 2024; Cairns et al., 2025). However, AAS's single-element limitation, narrower dynamic range, and longer analytical cycle render it less efficient for large-scale import surveillance programs. The use of autosamplers and platform atomizers has reduced these limitations, but ICP-MS remains efficient in sample throughput and better inter-laboratory comparability. However, matrix effects resulting from ions or organic residues can affect the accuracy of both techniques. Matrix-matched calibration, internal standards (Rhodium-103, Indium-115), and collision/reaction cell technologies (in ICP-MS) are essential for the removal of polyatomic interferences and ensuring trace-level accuracy (Balaram et al., 2025; Vanhaecke, 2025).

4.3. Influence of Acid Composition and Digestion Parameters

The chemistry of digestion has a direct effect on analyte recovery, especially for refractory or volatile elements. Nitric acid (HNO_3) remains the main oxidizing acid due to its strong oxidizing ability and low residual contamination. The addition of hydrogen peroxide (H_2O_2) speeds up the oxidation of organic matter, while hydrochloric acid (HCl) promotes solubilization of chloride-forming metals such as Hg and Ag (Okieke, 2017). However, the excessive use of HCl can introduce spectral interferences (e.g., $^{40}\text{Ar}^{35}\text{Cl}^+$ overlapping with $^{75}\text{As}^+$ in ICP-MS), making it necessary to optimize reagent ratios and collision/reaction gas technologies (Balaram, 2021). Research conducted by Santol et al. (2019) and Castro et al. (2022) showed that a 4:1 ratio of $\text{HNO}_3\text{:H}_2\text{O}_2$ achieved optimal recovery ($>98\%$) in all food matrices tested with no detectable interferences (Santos et al., 2019; Castro-González et al., 2022). The correlation between digestion temperature and recovery efficiency ($r > 0.9$) indicates that precise thermal control, only possible through microwave systems, is essential for accurate quantification (Kalinke et al., 2022; Anil et al., 2024).

4.4. Inter-Laboratory Variability and Standardization Issues

Despite technological progress, methodological discrepancies persist across different laboratories. Variations in digestion protocols (acid ratios, ramping profiles), reagent purity, and calibration strategies contribute to differences in recovery and detection limits (Shastak et al., 2024). From these differences, inter-laboratory studies organized under the AOAC and ISO frameworks have revealed variabilities of up to 15% in Pb and Cd concentrations when non-standardized digestion parameters were applied (Wale, 2024). The EPA Method 3052 and the AOAC 2015.01 offer unified methods for microwave digestion and trace metal measurement; however, compliance remains uneven worldwide, particularly in underdeveloped countries (Garzón et al., 2020; Xing, 2022). The establishment of uniform analytical validation methods, including recovery testing with CRMs and uncertainty measurement, continues to be important for ensuring data comparability across regulatory jurisdictions (Abram et al., 2025; Oros et al., 2025b). Instrument drift, plasma stability, and contamination from either laboratory air or reagents can distort results. Regular instrument calibration using multi-element standards, blank correction, and routine participation in proficiency testing (PT) programs are essential for maintaining analytical quality (Balaram and Satyanarayanan, 2022).

4.5. Heavy Metal Levels and Regulatory Compliance

Most analyzed imported foods had metal concentrations below U.S. regulatory limits, demonstrating the effectiveness of current import inspection and supplier auditing systems. However, the high mercury levels in fish and cadmium in cocoa powder, as seen in this review, indicate persistent contamination points where bioaccumulation and soil geochemistry in production areas play a role (Anyimah-Ackah et al., 2019; Frimpong et al., 2025). The FDA's ongoing risk assessment program, especially under the Closer to Zero initiative, emphasizes the need for accurate trace-level measurements in foods consumed by sensitive groups such as babies and pregnant women (Basak et al., 2023; Thenuwara et al., 2024; Riviere, 2025). The alignment of measured concentrations with regulatory standards confirms that microwave digestion followed by ICP-MS or AAS provides the necessary sensitivity and reliability for compliance testing. However, some limitations remain. Total metal analysis does not distinguish species-specific forms (e.g., inorganic vs. methylated As or Hg). The absence of a standardized reporting format among laboratories makes data interpretation difficult, and limited access to ICP-MS in low-income regions hampers consistent global monitoring (Clough et al., 2017; Regnell and Watras, 2018; Luvonga et al., 2020).

4.6. Emerging Analytical Innovations

Recent innovations aim to enhance throughput, sensitivity, and environmental sustainability in trace metal analysis. Technologies such as microwave-induced plasma optical emission spectrometry (MIP-OES) and ICP-MS/MS (triple quadrupole systems) enable ultra-trace detection with enhanced interference removal (Gonçalves et al., 2017; Tian et al., 2024; de Oliveira et al., 2025). The use of miniaturized closed-vessel microwave systems has allowed in situ digestion of small food samples (≤ 0.2 g) with reduced acid consumption and very short cycles (< 10 minutes), supporting green analytical chemistry principles (Ferrara et al., 2023; Sheehan and Furey, 2024). The introduction of hybrid sample systems (ultrasonic nebulizers and desolvation interfaces) has resulted in enhanced plasma efficiency, less matrix suppression, and improved signal stability (Jankowski, 2023; Dong et al., 2023). Regulatory automation and data integration with Laboratory Information Management Systems (LIMS) are improving traceability and compliance documentation. The continuous collaboration of laboratories between regulatory bodies, universities, and industries remains essential for developing reference methods for food safety that are accepted worldwide.

5. Conclusion

This review analyzed the efficiency of microwave-assisted digestion (MAD) followed by ICP-MS and AAS for the quantification of heavy metals in imported food commodities with emphasis on method optimization, analytical performance, and compliance with U.S. regulations. Microwave-assisted digestion showed excellent completeness of digestion, reduced sample preparation time, and minimized contamination risk compared to conventional open-vessel methods. The combined use of ICP-MS and AAS enabled precise, accurate, reproducible, and sensitive quantification of toxic metals such as Pb, Cd, Hg, and As in different food matrices, meeting the detection requirements set by the U.S. FDA, EPA, and Codex Alimentarius standards. The review points out that while ICP-MS remains the analytical benchmark due to its multi-element capability and its sub-ppb level sensitivity, AAS (especially GFAAS) continues to be a suitable low-cost alternative in laboratories with limited resources. The standardization of methods through EPA Method 3052 and AOAC 2015.01 is essential to minimize variability between laboratories. Regulatory compliance assessments confirm that most of the imported food products are within the allowable limits; however, regions with contamination of fish and cocoa emphasize the necessity for continuous monitoring and species-specific metal speciation studies. Future directions should focus on the combination of green digestion chemistry, automated speciation techniques, and global harmonization of regulatory frameworks to ensure equitable food safety across

borders. The MAD–ICP–MS/AAS workflow continues to be a vital part of modern analytical strategies for monitoring trace metals in the global food trade.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

- [1] Abdelmonem, B. H., Kamal, L. T., Elbaz, R. M., Khalifa, M. R. & Abdelnaser, A. (2025). From contamination to detection: The growing threat of heavy metals. *Heliyon*, p.11.
- [2] Abram, S.-L., Tavernaro, I., Johnston, L., Zou, S. & Resch-Genger, U. (2025). Nanoscale reference and test materials for the validation of characterization methods for engineered nanomaterials—current state, limitations, and needs. *Analytical and Bioanalytical Chemistry*, 417, p.2405-2425.
- [3] Abt, E. & Robin, L. P. (2020). Perspective on cadmium and lead in cocoa and chocolate. *Journal of Agricultural and Food Chemistry*, 68, p.13008-13015.
- [4] Adesina, K. E., Burgos, C. J., Grier, T. R., Sayam, A. S. & Specht, A. J. (2025). Ways to measure metals: From icp-ms to xrf. *Current Environmental Health Reports*, 12, p.7.
- [5] Adhikari, S. & Struwig, M. (2024). Concentrations and health risks of selected elements in leafy vegetables: A comparison between roadside open-air markets and large stores in johannesburg, south africa. *Environmental monitoring and assessment*, 196, p.170.
- [6] Alhagri, I. A. & Albeshry, M. (2023). Microwave-assisted digestion using dilute nitric acid and hydrogen peroxide for multielement determination in wheat flour by icp-ms. *Journal of Chemistry*, 2023, e2349838.
- [7] AlJuhaime, F., Kulluk, D. A., Yilmaz, F. G., Ahmed, I. A. M., Özcan, M. M. & Albakry, Z. (2025). Quantitative determination of minerals and toxic elements content in tropical and subtropical fruits by microwave-assisted digestion and icp-oes. *Biological Trace Element Research*, 203, p.1676-1684.
- [8] Alrashdi, M. M., Ragazzon-Smith, A., Strashnov, I. & Polya, D. A. (2024). Chemical analysis of toxic elements: Total cadmium, lead, mercury, arsenic and inorganic arsenic in local and imported rice consumed in the kingdom of saudi arabia. *Environmental geochemistry and health*, 46, p.518.
- [9] Alsehli, B. R. (2021). Evaluation and comparison between a conventional acid digestion method and a microwave digestion system for heavy metals determination in mentha samples by icp-ms. *Egyptian Journal of Chemistry*, 64, p.869-881.
- [10] Anil, A. S., Alam, S. & Thakur, L. K. (2024). Optimized mercury speciation analysis using lc-icp-ms and microwave assisted extraction for precise determination of methylmercury in fish, rice and soil. *Journal of Food Composition and Analysis*, 129, e106092.
- [11] Anyimah-Ackah, E., Ofosu, I. W., Lutterodt, H. E. & Darko, G. (2019). Exposures and risks of arsenic, cadmium, lead, and mercury in cocoa beans and cocoa-based foods: A systematic review. *Food Quality and Safety*, 3, p.1-8.
- [12] Asantewaa Adjei-Sah, O. and Is-mail, M. (2025). Advanced Chromatographic and Spectroscopic Techniques for the Analysis of Emerging Contaminants and Non-Nutritive Sweeteners in Ready-to-Drink Beverages. *Journal of Innovative Science*, 1, pp. 55-63.
- [13] Asantewaa Adjei-Sah, O. and Oduro, A.A., (2025). Systematic Assessment of Analytical Techniques for The Trace-Level Detection of Per- And Polyfluoroalkyl Substances (Pfas) In Complex Environmental and Biological Matrices. *EPRA International Journal of Research and Development*, 10, pp. 376-387.
- [14] Asher, A. S., Samuel, K. E. & Mary, D. S. (2020). Analytical method for comparison of suitable wet digestion methods for heavy metal analysis in soil around a cement industry. *Int. J. Res. Innov. Sci*, 7, p.41-47.
- [15] Baccaro, A. L. B., Gaubeur, I. & da Silva Felix, F. (2025). Analytical techniques for the determination of elemental composition of coffee. *Brazilian Journal of Analytical Chemistry*, 12, p.37-85.

- [16] Bacon, J. R., Butler, O. T., Cairns, W. R., Cavoura, O., Cook, J. M., Davidson, C. M. & Mertz-Kraus, R. (2024). Atomic spectrometry update—a review of advances in environmental analysis. *Journal of Analytical Atomic Spectrometry*, 39, p.11-65.
- [17] Bair, E. C. (2022). A narrative review of toxic heavy metal content of infant and toddler foods and evaluation of united states policy. *Frontiers in Nutrition*, 9, p.919913.
- [18] Baksi, S., Pal, P. & Baksi, S. 2025. Green valorization protocols for marine food waste: Collagen and chitin recovery. *Food waste valorization: Green techniques in sustainable management*. Springer.
- [19] Balaram, V. & Satyanarayanan, M. (2022). Data quality in geochemical elemental and isotopic analysis. *Minerals*, 12, p.999.
- [20] Balaram, V. (2021). Strategies to overcome interferences in elemental and isotopic geochemical analysis by quadrupole inductively coupled plasma mass spectrometry: A critical evaluation of the recent developments. *Rapid Communications in Mass Spectrometry*, 35, p.9065.
- [21] Balaram, V., Glorie, S., Gilbert, S. E. & Perumalsamy, C. (2025). Geochemical, geochronological, and environmental applications of tandem inductively coupled plasma mass spectrometry (icp-ms/ms): A review. *Environmental Earth Sciences*, 84, p.1-30.
- [22] Basak, S., Lewis, J., Vemula, S. R. & Halady, P. S. 2023. Safety and risk assessment of food items. *Biomedical applications and toxicity of nanomaterials*. Springer.
- [23] Bian, Y., Zhang, Y., Zhou, Y., Wei, B. & Feng, X. (2023). Recent insights into sample pretreatment methods for mycotoxins in different food matrices: A critical review on novel materials. *Toxins*, 15, p.215.
- [24] Bizzi, C., Pedrotti, M., Silva, J., Barin, J., Nóbrega, J. & Flores, E. (2017). Microwave-assisted digestion methods: Towards greener approaches for plasma-based analytical techniques. *Journal of Analytical Atomic Spectrometry*, 32, p.1448-1466.
- [25] Butcher, D. J. (2024). Recent advances in graphite furnace atomic absorption spectrometry: A review of fundamentals and applications. *Applied Spectroscopy Reviews*, 59, p.247-275.
- [26] Cairns, W. R., Butler, O. T., Cavoura, O., Davidson, C. M., Todolí-Torró, J.-L. & von der Au, M. (2025). Atomic spectrometry update—a review of advances in environmental analysis. *Journal of Analytical Atomic Spectrometry*.
- [27] Castro-González, N. P., Pérez-Sato, M., Soni-Guillermo, E., Valencia-Franco, E. & Carmona-Victoria, M. (2022). Nitric acid and hydrogen peroxide in milk and cheese digestion for the detection of metals. *Agro Productividad*, 15, p.61-70.
- [28] Chavhan, N. & Gawande, G. (2025). Emerging chemical oxygen demand detection techniques for wastewater: Advances in sustainable analytical methods. *Water, Air, & Soil Pollution*, 236, p.1-40.
- [29] Clough, R., Harrington, C. F., Hill, S. J., Madrid, Y. & Tyson, J. F. (2017). Atomic spectrometry update: Review of advances in elemental speciation. *Journal of Analytical Atomic Spectrometry*, 32, p.1239-1282.
- [30] Csontos, D., Kovács, L., Lengyel, K. & Bencs, L. (2025). High-resolution graphite furnace atomic absorption spectrometry determination of bismuth in lithium niobate optical crystals. *ACS omega*.
- [31] de Oliveira, P. B., Krause, M., Vieira, L. V., Moreira, L. S., Virgilio, A., Brandão, G. P. & Carneiro, M. T. W. D. (2025). Multi-isotope calibration strategy for trace elements determination in whole blood by inductively coupled plasma mass spectrometry. *Microchemical Journal*, 213, p.113628.
- [32] Dong, J., Liu, J., Xing, P., Li, S., Piao, J., Tao, H., Li, L., Zheng, H., Zhang, Z. & Han, S. (2023). High-efficiency miniaturized ultrasonic nebulization sample introduction system for elemental analysis of microvolume biological samples by inductively coupled plasma quadrupole mass spectrometry. *Analytical Chemistry*, 95, p.6271-6278.
- [33] Einolghozati, M., Talebi-Ghane, E., Khazaei, M. & Mehri, F. (2023). The level of heavy metal in fresh and processed fruits: A study meta-analysis, systematic review, and health risk assessment. *Biological Trace Element Research*, 201, p.2582-2596.
- [34] Ferrara, D., Beccaria, M., Cordero, C. E. & Purcaro, G. (2023). Microwave-assisted extraction in closed vessel in food analysis. *Journal of Separation Science*, 46, p.2300390.

- [35] Fischer, L., Moser, B. & Hann, S. (2021). Determination of background concentrations of ag, pd, pt and au in highly mineralized ground waters at sub-ng l⁻¹ concentrations by online matrix separation/pre-concentration coupled to icp-sfms. *Molecules*, 26, p.7253.
- [36] Fontoura, B. M., Judd, N., Schmittling, M., Gross, M. D., Jones, B. T. & Donati, G. L. (2025). Diluted acid and microwave-assisted extraction for trace element determination in biochar by icp oes and icp-ms. *Brazilian Journal of Analytical Chemistry*, 12, p.213-229.
- [37] Foreman, W. T., Williams, T. L., Furlong, E. T., Hemmerle, D. M., Stetson, S. J., Jha, V. K., Noriega, M. C., Decess, J. A., Reed-Parker, C. & Sandstrom, M. W. (2021). Comparison of detection limits estimated using single-and multi-concentration spike-based and blank-based procedures. *Talanta*, 228, p.122139.
- [38] Frimpong, E., Ankapong, E., Boakye, K. O., Ansah, E., Gyamfi, O., Barnes, B., Dodd, M. & Darko, G. (2025). Uptake and in-vitro bioaccessibility of toxic metals in cocoa beans: Human health risks. *Environmental geochemistry and health*, 47, p.33.
- [39] Garzón, D. A., Ahumada, D. A., Gamba, J. P. A., Ágreda, J. & Castillo, E. (2020). Quantification of arsenic, cadmium, mercury and lead in pineapple: Method development, validation and evaluation of in-house reference materials. *Journal of the Brazilian Chemical Society*, 31, p.1296-1305.
- [40] Gonçalves, D. A., Soncin, A. C., Donati, G. L. & Dos Santos, M. C. (2017). Determination of trace elements in cow placenta by tungsten coil atomic emission spectrometry. *Biological Trace Element Research*, 178, p.228-234.
- [41] Gonçalves, J. C. M. 2023. *Icp-ms-based methods for quantification and speciation of metals in remediated soils*. Universidade do Porto (Portugal).
- [42] Ignatavičius, G., Unsal, M. H., Busher, P., Wołkowicz, S., Satkūnas, J., Šulijienė, G. & Valskys, V. (2022). Geochemistry of mercury in soils and water sediments. *AIMS environmental science*, 9, p.261-281.
- [43] Ingallina, C., Spano, M., Prencipe, S. A., Vinci, G., Di Sotto, A., Ambroselli, D., Vergine, V., Crestoni, M. E., Di Meo, C. & Zoratto, N. (2025). Enhancing human health through nutrient and bioactive compound recovery from agri-food by-products: A decade of progress. *Nutrients*, 17, p.2528.
- [44] Ismail, S. A. & Afify, A. S. (2022). Validation and measurement uncertainty of rapid and simultaneous determination of 19 elements in drinking water using icp-ms. *Accreditation and Quality Assurance*, 27, p.299-311.
- [45] Jankowski, K. 2023. Ultrasonic nebulizers. *Analytical nebulizers*. Elsevier.
- [46] Juyal, V. K., Kandpal, H., Thakuri, S. C., Sailani, P., Prakash, O., Nand, V. & Gaurav, K. 2025. Recent uses of aas/icpms and its advancements for environment sustainability. *Modern spectroscopic techniques for drug discovery and environmental sustainability*. IGI Global Scientific Publishing.
- [47] Kalinke, I., Kubbutat, P., Taghian Dinani, S., Ambros, S., Ozelik, M. & Kulozik, U. (2022). Critical assessment of methods for measurement of temperature profiles and heat load history in microwave heating processes—a review. *Comprehensive Reviews in Food Science and Food Safety*, 21, p.2118-2148.
- [48] Kamalasekaran, K. & Sundramoorthy, A. K. (2024). Applications of chemically modified screen-printed electrodes in food analysis and quality monitoring: A review. *RSC advances*, 14, p.27957-27971.
- [49] Lao, Y. M., Qu, C. L., Zhang, B. & Jin, H. (2023). Development and validation of single-step microwave-assisted digestion method for determining heavy metals in aquatic products: Health risk assessment. *Food chemistry*, 402, p.134500.
- [50] Lata, S. & Ansari, N. G. 2024. Analytical techniques for heavy metal analysis. *Heavy metal contamination in the environment*. CRC Press.
- [51] Li, W., Li, Z. & Jennings, A. (2019). A standard-value-based comparison tool to analyze us soil regulations for the top 100 concerned pollutants. *Science of The Total Environment*, 647, p.663-675.
- [52] Li, X., Liu, T., Chang, C., Lei, Y. & Mao, X. (2021). Analytical methodologies for agrometallomics: A critical review. *Journal of Agricultural and Food Chemistry*, 69, p.6100-6118.
- [53] Luvonga, C., Rimmer, C. A., Yu, L. L. & Lee, S. B. (2020). Analytical methodologies for the determination of organoarsenicals in edible marine species: A review. *Journal of Agricultural and Food Chemistry*, 68, p.1910-1934.
- [54] Ma, J., Zheng, J. & Chen, J. (2025). Critical mechanistic insight, technological innovation advances and multi-media environmental application of colorimetry toward heavy metal detection. *Critical Reviews in Analytical Chemistry*, p.1-33.

- [55] Mishra, S., Singh, G., Gupta, A. & Tiwari, R. K. 2023. Heavy metal/metalloid contamination: Their sources in environment and accumulation in food chain. *Heavy metal toxicity: Environmental concerns, remediation and opportunities*. Springer.
- [56] Mititelu, M., Neacșu, S. M., Busnatu, Ș. S., Scafa-Udriște, A., Andronic, O., Lăcraru, A.-E., Ioniță-Mîndrican, C.-B., Lupuliasa, D., Negrei, C. & Olteanu, G. (2025). Assessing heavy metal contamination in food: Implications for human health and environmental safety. *Toxics*, 13, p.333.
- [57] Mukherjee, A. G., Renu, K., Gopalakrishnan, A. V., Veeraraghavan, V. P., Vinayagam, S., Paz-Montelongo, S., Dey, A., Vellingiri, B., George, A. & Madhyastha, H. (2023). Heavy metal and metalloid contamination in food and emerging technologies for its detection. *Sustainability*, 15, p.1195.
- [58] Munir, N., Jahangeer, M., Bouyahya, A., El Omari, N., Ghchime, R., Balahbib, A., Aboulaghras, S., Mahmood, Z., Akram, M. & Ali Shah, S. M. (2021). Heavy metal contamination of natural foods is a serious health issue: A review. *Sustainability*, 14, p.161.
- [59] Munjanja, B. K., Salami, O. S., Mashale, K. N., Nomngongo, P. N. & Mketi, N. (2025). Multivariate optimization of a green microwave-assisted hydrogen peroxide digestion of vegetable oils and subsequent elemental determination via inductively coupled plasma–optical emission spectrometry. *Food Analytical Methods*, 18, p.161-171.
- [60] Nassour, C., Zacharauskas, Z., Nabhani-Gebara, S., Barton, S. J. & Barker, J. (2022). Development and validation of an icp-ms method for the detection of platinum in the lebanese aquatic environment. *Water*, 14, p.2631.
- [61] Okieke, O. 2017. *Effect of food chain mediated exposure to cadmium and arsenic on some oxidative stress markers in rat models*. Delta State University, Abraka.
- [62] Oloruntoba, A., Omoniyi, A. O., Shittu, Z. A., Ajala, R. O. & Kolawole, S. A. (2024). Heavy metal contamination in soils, water, and food in nigeria from 2000–2019: A systematic review on methods, pollution level and policy implications. *Water, Air, & Soil Pollution*, 235, p.586.
- [63] Oros, A., Coatu, V., Oleinik, Y., Atabay, H., Aslan, E., Bat, L., Machitadze, N., Bucse, A., Çağlar Balkis, N. & Ersoy Korkmaz, N. 2025a. Toward harmonized black sea contaminant monitoring: Bridging methods and assessment. *Water* 2025, 17, p.3107.
- [64] Oros, A., Coatu, V., Oleinik, Y., Atabay, H., Aslan, E., Bat, L., Machitadze, N., Bucse, A., Çağlar Balkis, N. & Ersoy Korkmaz, N. (2025b). Toward harmonized black sea contaminant monitoring: Bridging methods and assessment. *Water*, 17, p.3107.
- [65] Ozbek, N., Ustabasi, G. S. & Akman, S. (2015). Direct determination of lead in plastic toys by solid sampling high resolution-continuum source graphite furnace atomic absorption spectrometry. *Journal of Analytical Atomic Spectrometry*, 30, p.1782-1786.
- [66] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A. & Brennan, S. E. (2021). The prisma 2020 statement: An updated guideline for reporting systematic reviews. *bmj*, p.372.
- [67] Parker, G. H., Gillie, C. E., Miller, J. V., Badger, D. E. & Kreider, M. L. (2022). Human health risk assessment of arsenic, cadmium, lead, and mercury ingestion from baby foods. *Toxicology reports*, 9, p.238-249.
- [68] Patriarca, M., Barlow, N., Cross, A., Hill, S., Milde, D. & Tyson, J. (2025). Atomic spectrometry update: Review of advances in the analysis of clinical and biological materials, foods and beverages. *Journal of Analytical Atomic Spectrometry*.
- [69] Patriarca, M., Barlow, N., Cross, A., Hill, S., Robson, A. & Tyson, J. (2023). Atomic spectrometry update: Review of advances in the analysis of clinical and biological materials, foods and beverages. *Journal of Analytical Atomic Spectrometry*, 38, p.496-577.
- [70] Patriarca, M., Barlow, N., Cross, A., Hill, S., Robson, A., Taylor, A. & Tyson, J. (2022). Atomic spectrometry update: Review of advances in the analysis of clinical and biological materials, foods and beverages. *Journal of Analytical Atomic Spectrometry*, 37, p.410-473.
- [71] Pohl, P., Greda, K., Welna, M., Jamroz, P., Dzimitrowicz, A. & Szymczycha-Madeja, A. (2024). The development and validation of a new method for the fast determination of al, ba, ca, cu, fe, k, mg, mn, na, sr and zn in rice by inductively coupled plasma optical emission spectrometry. *Analytical Methods*, 16, p.4187-4197.

- [72] Provete, C. S., Dalfior, B. M., Mantovaneli, R., Carneiro, M. T. W. & Brandão, G. P. (2024). Comparison of the performance of icp-ms, cv-icp-oes, and tda aas in determining mercury in marine sediment samples. *ACS omega*, 9, p.49229-49238.
- [73] Regnell, O. & Watras, C. J. (2018). Microbial mercury methylation in aquatic environments: A critical review of published field and laboratory studies. *Environmental Science & Technology*, 53, p.4-19.
- [74] Riviere, J. E. 2025. Food safety. *Zero—much to do about nothing?* : Springer.
- [75] Saber, A., Malhat, F., Saber, E.-S. & Shokr, S. A. (2025). Optimised determination of arsenic and lead in tea samples using microwave-assisted digestion and icp-ms: Method validation and health risk assessment. *International Journal of Environmental Analytical Chemistry*, p.1-16.
- [76] Saber, A., Malhat, F., Saber, E.S. and Shokr, S.A., 2025. Optimised determination of arsenic and lead in tea samples using microwave-assisted digestion and ICP-MS: method validation and health risk assessment. *International Journal of Environmental Analytical Chemistry*, pp.1-16.
- [77] Sader, J. A. & Ryan, S. (2020). Advances in icp-ms technology and the application of multi-element geochemistry to exploration. *Geochemistry: exploration, environment, analysis*, 20, p.167-175.
- [78] Sandström, V., Huan-Niemi, E., Niemi, J. & Kumm, M. (2024). Dependency on imported agricultural inputs—global trade patterns and recent trends. *Environmental Research: Food Systems*, 1, p.015002.
- [79] Santos, H. M., Coutinho, J. P., Amorim, F. A. C., Lobo, I. P., Moreira, L. S., Nascimento, M. M. & de Jesus, R. M. (2019). Microwave-assisted digestion using diluted hno₃ and h₂o₂ for macro and microelements determination in guarana samples by icp oes. *Food chemistry*, 273, p.159-165.
- [80] Schlemmer, G. & Hinds, M. (2025). 1 fundamentals for the chemical measurement process. *Elemental Analysis: ICP-MS, ICP-OES, AAS, XRF*, p.1.
- [81] Serafim, W. K. M., Torres, B. S. S., Kunst, T. H., do Nascimento, A. L. S., da Silva, I. J. S., de Almeida, M. & Ribeiro, A. P. S. P. (2024). Mineral composition of rice, carrots, and chayote after microwave-assisted decomposition using diluted nitric acid. *Brazilian Journal of Analytical Chemistry*, 11, p.102-117.
- [82] Sharma, M., Kant, R., Sharma, A. & Sharma, A. (2025). Exploring the impact of heavy metals toxicity in the aquatic ecosystem. *International Journal of Energy and Water Resources*, 9, p.267-280.
- [83] Shastak, Y., Pelletier, W. & Kuntz, A. (2024). Insights into analytical precision: Understanding the factors influencing accurate vitamin a determination in various samples. *Analytica*, 5, p.54-73.
- [84] Sheehan, A. & Furey, A. (2024). Advanced review of the contributing factors for the microwave digestion of food matrices for trace elemental analysis. *Talanta open*, 9, p.100309.
- [85] Souza, J. P., Cerveira, C., Miceli, T. M., Moraes, D. P., Mesko, M. F. & Pereira, J. S. (2020). Evaluation of sample preparation methods for cereal digestion for subsequent as, cd, hg and pb determination by aas-based techniques. *Food chemistry*, 321, p.126715.
- [86] Taylor, A., Catchpole, A., Day, M. P., Hill, S., Martin, N. & Patriarca, M. (2020). Atomic spectrometry update: Review of advances in the analysis of clinical and biological materials, foods and beverages. *Journal of Analytical Atomic Spectrometry*, 35, p.426-454.
- [87] Thabit, T. M., Shokr, S. A., Elgeddawy, D. I. & El-Naggar, M. A. (2020). Determination of heavy metals in wheat and barley grains using icp-ms/ms. *Journal of AOAC International*, 103, p.1277-1281.
- [88] Thenuwara, G., Javed, B., Singh, B., Byrne, H. J. & Tian, F. (2024). Sex-and gender-specific considerations in mycotoxin screening: Assessing differential exposure, health impacts, and mitigation strategies. *Microbiology Research*, 15, p.2455-2492.
- [89] Tian, M., Zhang, H., Fan, H., Yin, M., Wang, W. & Shi, C. (2024). Method for determination of elemental impurities in metronidazole benzoate using inductively coupled plasma mass spectrometry. *European Journal of Mass Spectrometry*, 30, p.60-64.
- [90] Vanhaecke, F. (2025). 4 inductively coupled plasma-mass spectrometry (icp-ms). *Elemental Analysis: ICP-MS, ICP-OES, AAS, XRF*, p.278.
- [91] Vassileva, E., Mandjukov, P., Wrobel, K., Escobosa, A. R. C., Ojeda, A. G., Ruszczynska, A., Kurek, E., Dmitruk, W., Brozek-Mucha, Z. & Wycislik, A. 2017. *Inorganic trace analytics: Trace element analysis and speciation*, Walter de Gruyter GmbH & Co KG.

- [92] Vieira, A. L., de Carvalho, G. G. A., Neto, J. A. G., Oliveira, P. V., Kamogawa, M. Y. & Virgilio, A. (2024). A convective heated digestion system with closed vessels: A new digester for elemental inorganic analysis. *Journal of Analytical Atomic Spectrometry*, 39, p.356-363.
- [93] Vilela, T. M., Almeida, T. C. R., Souza, A. L. M. d., Joca, J. F. S., Oliveira, R. S., Batista, B. L., Baccaro, A. L. B., Gaubeur, I. & Felix, F. d. S. (2025). Analytical techniques for the determination of elemental composition of coffee. *Brazilian Journal of Analytical Chemistry*.
- [94] Wale, K. (2024). Comparisons of different digestion methods for heavy metal analysis from fruits. *Science Journal of Analytical Chemistry*, 12, p.7-12.
- [95] Xie, A. & Wu, W. (2025). Emerging nanosensor technologies for the rapid detection of heavy metal contaminants in agricultural soils. *Analytical Methods*.
- [96] Xing, L. 2022. Determination of toxic elements in food following aoac method 2015.01 using the nexion icp-ms.