

COMPARATIVE EVALUATION OF ANALYTICAL TOOLS FOR FOOD QUALITY AND SAFETY: FOCUS ON NAA AND ICP-OES

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ABSTRACT

Elemental analysis plays a critical role in food quality control, safety assessment, and nutritional evaluation by quantifying trace elements essential for health or potentially toxic at elevated levels. Neutron Activation Analysis (NAA) and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) are two of the most popular analytical techniques because of their reliability and sensitivity. This study aims to compare NAA and ICP-OES in terms of analytical performance, sample preparation, detection limits, and practical applicability in food analysis. The findings indicate that NAA offers high accuracy and minimal sample preparation, particularly advantageous for multi-elemental analysis of solid samples without chemical digestion. However, it requires access to a nuclear reactor and has longer turnaround times. In contrast, ICP-OES is more accessible and faster, with high throughput and suitable for routine analysis of liquid samples, although it may require complex sample digestion and can suffer from spectral interferences. The complementary nature of both methods suggests their application depends on specific analytical requirements, such as the matrix type, element of interest, and available infrastructure.

1. INTRODUCTION

Despite being needed in very small amounts, trace elements are essential for human nutrition and health. Numerous physiological processes, such as enzyme activity, immunological response, antioxidant defense, and hormone control, depend on essential trace elements like iron (Fe), zinc (Zn), selenium (Se), copper (Cu), and iodine (I). Deficiencies in these elements can lead to serious health issues such as anemia, impaired cognitive development, weakened immunity, and metabolic disorders. Conversely, certain trace elements may be hazardous in high concentrations. Certain elements, such

arsenic (As), cadmium (Cd), lead (Pb), and mercury (Hg), can cause serious health problems, such as renal damage, neurological impairment, and an elevated risk of cancer. These toxic elements can enter the food chain through environmental contamination, agricultural practices, or food processing. By their dual nature (both beneficial and harmful) determination of trace elements in food is essential for ensuring nutritional adequacy and food safety. There are some analytical techniques for determination of trace elements; (i.e.; NAA, ICP-OS etc). The determination and regulation of trace elements in food, water, and the environment are essential for

protecting public health. Several key international and regional organizations play vital roles in establishing guidelines, setting permissible limits, and promoting harmonized analytical methods for trace elements. The European Food Safety Authority (EFSA), the Codex Alimentarius Commission (Codex), and the World Health Organization (WHO) are some of the most powerful regulatory forces. WHO provides global health guidelines, including tolerable intake levels for essential and toxic trace elements based on risk assessments and scientific evidence. Codex, which is established by WHO and FAO, develops international food standards, including maximum levels (MLs) for contaminants such as heavy metals and trace elements to facilitate fair trade and ensure food safety & also EFSA offers scientific advice and conducts risk assessments for the European Union, evaluating exposure levels, toxicological profiles, and dietary intake of trace elements to inform regulatory decisions and public policy. Together, these regulatory bodies shape the global framework for monitoring, assessing, and controlling trace element concentrations, ensuring consumer protection and environmental sustainability.

Accurate and reliable quantification of trace elements in food demands analytical techniques that can manage complex sample matrices, detect elements at ultra-trace levels, and process large numbers of samples efficiently. Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) and Neutron Activation Analysis (NAA) address these issues in different ways than any other analytical tool, each with its own advantages and disadvantages. In terms of accuracy, NAA is known for its exceptional accuracy, especially for trace and ultra-trace elements. It is a primary ratio method, meaning it doesn't require

calibration with standards. Accuracy is minimally affected by the sample matrix. Not only NAA, the ICP-OES is also known for its high accuracy for a broad range of elements, particularly in the mid to high concentration range (ppm to high ppb). It relies heavily on external calibration, requiring high-quality standards and strict quality control. Accuracy may be compromised by matrix interferences and incomplete digestion, particularly for solid or fatty samples. A major advantage of NAA is its near-complete independence from matrix effects. Since the analysis is based on nuclear properties rather than chemical behavior, complex food matrices (e.g., high-fat, fibrous, or protein-rich samples) do not significantly interfere. No digestion or chemical treatment is needed, preserving the integrity of volatile or sensitive elements. In case of ICP-OES, highly susceptible to matrix effects, which can result in signal enhancement or suppression and also it requires careful sample digestion (usually with nitric acid or microwave-assisted digestion), which can introduce variability or loss of volatile elements (e.g., As, Se). The comparison of Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) and Neutron Activation Analysis (NAA) is crucial because of their different but widely used applications in trace element analysis for food safety and quality control. Both techniques are well-established, yet they differ significantly in analytical principles, operational requirements, and suitability for various applications. NAA is a highly sensitive and non-destructive technique that excels in measuring ultra-trace elements in complex matrices without the need for chemical preparation. It is particularly valuable in research settings, forensic analysis, and reference laboratory applications. ICP-OES, on the other hand, is a widely accessible, high-throughput tool

ideal for routine screening of essential and toxic metals in foods. It is commonly used in regulatory testing, commercial food labs, and industrial quality control. Comparing these two methods helps clarify their relative advantages and limitations, including, Sensitivity and detection limits, Matrix tolerance, sample preparation needs, cost-effectiveness, Throughput and scalability. Different food testing scenarios—ranging from routine regulatory compliance to trace-level contamination assessment—require analytical methods tailored to their specific demands. The decision between NAA and ICP-OES often involves trade-offs between accuracy, efficiency, and infrastructure availability. A comparative analysis allows stakeholders to choose the most appropriate method for their analytical objectives. With increasing consumer demand for food transparency and tightening global regulations on heavy metals and micronutrient labeling, food laboratories need methods that are both precise and practical. This comparison provides a strategic framework for labs, policy makers, and researchers to align their analytical capabilities with emerging food safety and public health priorities. With a focus on their applicability to food quality and safety monitoring, this paper compares the analytical methods of Neutron Activation Analysis (NAA) and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) for determining trace elements in food.

2. PRINCIPLES OF ANALYTICAL TECHNIQUES

2.1 Neutron Activation Analysis (NAA)

2.1.1 Theory:

Based on the nuclear reaction that happens when stable isotopes in a sample are exposed to neutrons, usually from a nuclear reactor, neutron activation analysis (NAA)

is a sensitive, non-destructive analytical method. Upon capturing a neutron, these isotopes become unstable radioactive nuclei, which decay by emitting gamma rays that are characteristic of each element. High-resolution detectors (such as HPGe) can measure the energy and intensity of these gamma rays to precisely identify and quantify the components present in the sample. NAA is highly effective for multi-elemental analysis, especially in trace and ultra-trace quantification is extensively employed in disciplines like materials analysis, forensics, environmental science, and archaeology.

2.1.2 Principle:

When a stable nucleus is bombarded with thermal neutrons (usually from a nuclear reactor or neutron generator), it captures a neutron and forms a radioactive isotope. This newly formed unstable isotope decays to a more stable state by emitting gamma rays, which are characteristic of the specific element.

2.1.3 Instrumentation (reactors and detectors):

The neutron source is a critical component in NAA, as it provides the neutrons required for sample activation. The primary types of neutron sources used in NAA are nuclear reactors are the most common sources of neutrons for NAA. They offer a high neutron flux, which is necessary for effective sample activation. It is common practice to use research reactors like the Advanced Test Reactor (ATR) and the High Flux Isotope Reactor (HFIR). These reactors offer controlled environments with high neutron flux, allowing for precise and efficient activation. Radioisotope sources, such as Californium-252, emit neutrons through spontaneous fission. These sources are portable and convenient for field applications where access to a reactor is not

feasible. They offer lower neutron flux compared to reactors but are suitable for applications where high neutron flux is not critical. Particle accelerators produce neutrons through spallation or fusion reactions. Accelerators can generate tailored neutron energy spectra for specific applications. They provide flexibility in neutron energy and flux, making them suitable for specialized analyses. Accelerators are used in advanced research facilities for detailed neutron activation studies.

The detection of gamma rays emitted by activated samples is crucial for NAA. Gamma-Ray detectors measure the gamma rays emitted by activated samples. High-purity germanium (HPGe) and sodium iodide (NaI) detectors are common varieties. NaI detectors are cost-effective and widely used but have lower resolution compared to HPGe detectors. HPGe detectors provide superior energy resolution, which is essential for distinguishing closely spaced gamma-ray peaks. Although HPGe (High-Purity Germanium Detectors) detectors have better energy resolution, they are recommended for high-precision measurements. They require cooling, typically with liquid nitrogen to achieve optimal performance. HPGe detectors are essential for detailed spectral analysis and accurate quantification of elements. Scintillation detectors use scintillating materials to detect gamma rays. They offer moderate resolution and high efficiency, making them suitable for various applications. Scintillation detectors are less expensive than HPGe detectors and are used in routine analyses where high resolution is not critical.

2.1.4 Sample requirements and workflow

For accurate and safe analysis, specific

sample requirements must be met. Samples can be in solid, liquid, or powdered form, but must be homogenous and representative of the material being tested. Typically, 10–500 mg of solid or powdered sample is sufficient, while 0.1–1 ml is required for liquids, depending on the expected concentration of target elements and the reactor's neutron flux. Samples must be clean and free from surface contaminants such as oils, dust, or biological residue to prevent interference during analysis. They should be placed in containers made of materials that do not become radioactive under neutron irradiation, such as quartz, polyethylene, Teflon, or aluminum. Volatile, explosive, or highly radioactive substances are not permitted unless approved under strict safety protocols. Proper labeling is essential; each sample must be uniquely identified using heat-resistant, non-contaminating labels. Accompanying documentation should include details such as sample ID, mass, matrix type, and any known elemental composition. Adhering to these requirements ensures the liability of analytical results and the safety of both the sample and personnel during the irradiation process.

Sample irradiation is a critical step in NAA, involving the exposure of the sample to neutrons to induce radioactivity. Selecting Neutron Flux and Irradiation Facilities with the appropriate neutron flux is crucial for efficient activation. High-flux reactors or specialized neutron sources are commonly used. The activation efficiency is determined by the neutron flux, which is expressed in neutrons per square centimeter per second ($n/cm^2/s$). Higher fluxes lead to more efficient activation and shorter irradiation times. Optimizing irradiation time and conditions is essential for accurate results. Factors such as neutron flux, sample

size, and desired sensitivity are considered. Irradiation times can range from seconds to hours, depending on the element and the required sensitivity. Proper optimization helps balance sensitivity and isotope interference.

Post-irradiation handling ensures accurate measurement and minimizes interference allowing for the decay of short-lived isotopes before measurement reduces background radiation and enhances accuracy. The decay period depends on the half-lives of the isotopes of interest. Adequate cooling and decay periods are crucial for distinguishing between different isotopes and minimizing interference. Safe handling and secure storage prevent contamination or loss. Proper storage conditions ensure sample integrity. Shielded containers and remote handling tools are used to protect personnel from radiation exposure. Storage conditions help maintain the sample's radioactivity at desired levels for accurate analysis.

2.1.5 Gamma- Ray Spectroscopy:

Gamma-ray spectroscopy involves measuring the gamma rays emitted by activated samples. Ensuring detectors are calibrated for accurate energy measurements. Calibration involves using known standards to establish calibration curves. Regular calibration maintains accuracy and reliability. The capacity to resolve closely spaced gamma-ray peaks depends on the detector's energy resolution. Analyzing spectra to identify characteristic gamma peaks and determine concentrations. Peak fitting algorithms and background subtraction techniques enhance accuracy. Software tools automate this process, but expert review is often required for complex spectra. Accurate peak identification is crucial for reliable quantification of elements.

2.1.6 Quantitative Analysis:

Quantitative analysis involves calculating elemental concentrations in the sample. Using known standards and calibration curves to calculate concentrations. This involves comparing the sample's gamma-ray intensities with those of standards. Concentrations are determined based on gamma-ray intensity and the characteristics of the radioactive isotopes. Ensuring accuracy through comparison with certified reference materials. This helps validate the analysis and correct for systematic errors. Reference materials are selected based on their similarity to the sample matrix and known concentrations of elements. The use of standards ensures reliable and comparable results.

2.1.7 Report:

The elemental concentrations obtained by Neutron Activation Analysis (NAA) are usually expressed as parts per million (ppm) or parts per billion (ppb). The report includes identified elements, their measured quantities, and associated uncertainties to ensure accuracy and reliability.

2.2 Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)

2.2.1 Principle:

An injector tube inside the torch transports the sample aerosol into the plasma after it has been created in the proper nebulizer and spray chamber. Due to high temperature at Plasma region, the sample undergoes desolvation, vaporization, analyte emission is measured. From the wavelength, the element is identified. From the emission count, concentration of the analyte is determined.

2.1.2 Instrumentation:

The ICP-OES system comprises several essential components that work in

conjunction to perform elemental analysis based on optical emission spectroscopy. The key components are: Sample Introduction System, it includes a nebulizer and a spray chamber. The liquid sample is converted into an aerosol by the nebulizer and transported to the plasma via argon gas. The spray chamber filters out large droplets, ensuring that only fine aerosol reaches the plasma. Concentric quartz tubes make up the plasma torch. Concentric quartz tubes make up the plasma torch. A radiofrequency (RF) generator ionizes argon gas as it passes through these tubes, producing a high-temperature plasma (~6000–10,000 K). The atoms and ions in the sample are excited by this plasma, which results in the emission of distinctive light wavelength.

The radio frequency generator (typically operating at 27 or 40MHz) provides energy to ionize argon gas and maintain the plasma. It ensures stable and sustained plasma generation for consistent excitation of sample atoms. It consists of Optical System it works like the emitted light from the excited atoms/ions is collected and directed into a monochromator or polychromator system. This optical system disperses the light based on wavelength using diffraction gratings, allowing the detection of element-specific emission lines. Charge-coupled devices (CCDs) or photomultiplier tubes (PMTs) are used by contemporary ICP-OES systems to identify and measure the intensity of light emissions. Each element's concentration in the sample is directly correlated with the intensity. A computer-based system controls instrument parameters, performs calibration, processes the spectral data, and generates analytical results. Software often includes features for peak identification, interference correction, and quantitative analysis.

2.1.3 Sample preparation and digestion:

Sample preparation:

Proper sample preparation is a critical step in ensuring accurate, reliable, and reproducible results in ICP-OES analysis. The aim is to convert solid, semi-solid, or complex liquid matrices into a stable, homogeneous, and interference-free solution suitable for introduction into the plasma.

1. Sample Collection and Handling

Samples should be collected in clean, inert containers (e.g., poly propylene or Teflon) to avoid contamination. Storage conditions must prevent elemental loss or alteration, with refrigeration or acid preservation (usually with HNO₃) used when necessary. Homogenization of solid or heterogeneous samples is essential, typically using grinding, milling, or thorough mixing.

2. Drying and Weighing (for solids)

Solid samples are usually dried at 105°C (or as required for specific protocols) to remove moisture. A known weight (typically 0.1–1 g) is used for digestion, ensuring accuracy in final concentration calculations.

3. Sample digestion:

The goal of digestion is to break down complex matrices and convert the sample into a clear aqueous solution suitable for nebulization into the ICP.

Acid Digestion (Wet Digestion) is done by using nitric acid (HNO₃), sulfuric acid (H₂SO₄), hydrogen peroxide (H₂O₂), and hydrochloric acid (HCl) is effective for organic matrices (e.g., biological tissues, food). Performed in open vessels on hot plates or closed vessels in microwave digestion systems. Microwave-Assisted Digestion accelerates by applying heat and pressure in sealed vessels. Reduces digestion time and minimizes contamination. Ideal for high-throughput

labs and complex matrices. Fusion Digestion is suitable for refractory samples (e.g., minerals, ceramics). Involves mixing the sample with flux (e.g., lithium borate) and heating to form a molten mixture that dissolves upon cooling with acid or water.

4. Filtration and Dilution

Post-digestion, the solution is filtered to remove particulates using Whatman filters or 0.45 μm membrane filters. It could be required to dilute with acid or deionized water in order to bring analyte

concentrations within the instrument's operating range.

5. Internal Standards and Matrix Matching

To correct for potential matrix effects and instrument drift, internal standards (e.g., yttrium or scandium) are often added. Matrix-matched calibration standards improve accuracy in complex sample types.

3. COMPARISON PARAMETERS (Between NAA & ICP-OES)

Parameter	NAA	ICP-OES
Sensitivity	✓	✓✓
Destructiveness	No	Yes
Element range	Medium	Wide
Throughput	Low	High
Cost & accessibility	High	Moderate
Matrix interferences	Low	Moderate
Sample preparation	Minimal	Complex
Regulatory status	Reference use	Routine compliance

Table -1 Comparison parameters between NAA & ICP-OES

4. CASE STUDIES AND APPLICATIONS IN FOOD

4.1 Milk and Dairy Products

Calcium (Ca), Magnesium (Mg), and Zinc (Zn) are essential nutrients vital for bone development (Ca), enzymatic and neuromuscular functions (Mg), and immune support and tissue repair (Zn). Their levels in 25 dairy and nutritional products including milk, cheese, butter, and infant formula were analyzed using ICP-AES and ICP-MS, following ISO 15151:2018 and AOAC Method 2011.14, with microwave digestion to ensure matrix breakdown. The method showed high accuracy (98–101%

recovery using NIST SRM 1849a), good repeatability (2.2–3.9%), and reproducibility (6.0–12.2%) in fortified products, meeting AOAC SMPR 2014.004 criteria for regulatory use. Conversely, toxic elements like Lead (Pb) and Arsenic (As) pose serious health risks; Pb is neurotoxin, especially to children, and as is carcinogenic. Contamination sources include environmental pollution, animal feed, and processing materials. A study from Egypt reported Pb levels in dairy exceeding the Codex limit of 0.02 mg/kg, while a PLOS ONE meta-analysis found elevated cancer risk ($\text{CR} \geq 10^{-4}$) from Pb and as in milk from Pakistan, Brazil, and Egypt. Though non-carcinogenic risk (THQ) was

generally low (<1), some regions showed elevated CR, highlighting the need for stricter monitoring. ICP-MS with Kinetic Energy Discrimination (KED), using a Thermo Scientific iCAP RQ, was employed for precise detection, ensuring compliance with MRLs set by the EU, CFDA, and FSSAI.

4.2 Cereals and Legumes

In order to determine the geographical origin, botanical variety, or production methods (such as organic and conventional), elemental fingerprinting analyzes trace and ultra-trace elements in food products using sophisticated techniques like ICP-MS, ICP-OES, and Isotope Ratio Mass Spectrometry (IRMS). A European Commission study highlighted the effectiveness of combining multi-element profiles (e.g., Sr, Ba, Rb, Mn, Zn) with stable isotope ratios (e.g.: $\delta^{13}\text{C}$, $\delta^{14}\text{N}$, $\delta^{16}\text{O}$) to authenticate the origin of cereals like wheat and rice, using chemometric tools such as PCA and LDA for classification. This approach has practical applications in differentiating EU-grown vs. imported wheat, identifying Basmati vs. non-Basmati rice, and supporting traceability in lentils and pulses to combat fraud. Meanwhile, contaminant analysis focuses on toxic elements like Cadmium (Cd), which accumulates in the kidneys and liver and is associated with bone demineralization and cancer, and Mercury (Hg), a neurotoxin particularly harmful in its methylated form and especially dangerous during fetal development. Cd contamination stems from phosphate fertilizers, industrial emissions, and polluted irrigation water, while Hg primarily originates from atmospheric deposition and contaminated soils. For the detection of Cd and Hg in grains and pulses, the FSSAI guideline suggests atomic absorption spectrometry (AAS) and ICPMS. To ensure reliable analysis, sample preparation

includes acid digestion using hydrogen peroxide (H_2O_2) and nitric acid (HNO_3), followed by filtration and dilution.

4.3 Beverages (Wine, Tea)

Validation studies comparing analytical methods for authenticity and adulteration detection in products like wine and tea reveal that techniques fall in to two main categories: destructive methods (e.g., isotope ratio analysis, GC-MS, LC-MS, DNA-based techniques) and non-destructive methods (e.g., NIR, FTIR, Raman spectroscopy, NMR, imaging). A 2023 review in *Beverages* highlighted that while destructive methods offer high specificity and sensitivity ideal for identifying specific adulterants like synthetic dyes or added sugars, they are time-consuming and require extensive sample preparation. Non-destructive methods, in contrast, provide rapid, cost-effective screening suitable for high-throughput analysis but generally offer lower specificity unless combined with chemometric tools. The conclusion underscores that no single technique is universally superior; instead, hybrid approaches—such as combining spectroscopy with chemometrics or isotope analysis—yield the most robust results. In food fraud detection, wine is commonly adulterated through the addition of water, sugar, or synthetic alcohol, and mislabeling of grape variety or origin. Detection tools include SNIF-NMR for sugar adulteration via ethanol isotopic ratios, EA-IRMS for origin verification using $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, and LC-MS/MS for detecting illegal additives. Tea fraud, according to a 2024 *Trends in Food Science & Technology* review, includes unapproved enhancements (43% of cases), mislabeling of origin or grade, and use of filler leaves. Techniques such as mass spectrometry identify adulterant markers, while FTIR and NIR allow rapid screening

of powders. NMR and DNA bar coding confirm botanical authenticity, and electronic noses/sensors detect aroma deviations. An emerging trend is the integration of AI and chemo metrics to interpret complex spectral data, significantly enhancing the accuracy and reliability of fraud detection across food matrices

4.4 Spices, Seafood, Baby Food

Lead (Pb), Arsenic (As), Cadmium (Cd), and Mercury (Hg) are examples of ultra-trace metals that, even at very low concentrations, pose serious health risks. Lead and mercury are neurotoxic (methyl mercury being especially hazardous), As is carcinogenic (especially in its inorganic form), and Cd is known to build up in the kidneys and cause toxicity to the bones and reproductive system. These contaminants can infiltrate food through soil and water pollution, atmospheric deposition, agricultural inputs like fertilizers and pesticides, and contact with processing or packaging materials. Regulatory screening is strict, especially for vulnerable populations and high-risk foods. Under the U.S.FDA's Baby Food Safety Act of 2021, the limits are set at: inorganic arsenic ≤ 10 $\mu\text{g/kg}$, lead and cadmium ≤ 5 $\mu\text{g/kg}$ each, and mercury ≤ 2 $\mu\text{g/kg}$, with the EU and Codex often imposing comparable or even stricter limits based on the product category. Depending on the species, FSSAI and Codex limit the levels of methyl mercury, lead, and cadmium in seafood at 1.0–1.5 mg/kg, 0.3 mg/kg, and 0.1–0.5 mg/kg, respectively, in predatory fish. Because of the soil conditions, spices naturally acquire heavy metals. Codex-aligned levels of lead ≤ 2.0 mg/kg, cadmium ≤ 0.3 mg/kg, and arsenic ≤ 1.0 mg/kg are proposed in the 2025 ASTA recommendation. Regional and crop-specific variances, however, still provide difficulties for safety assurance and enforcement.

5. REGULATORY AND QUALITY ASSURANCE ASPECT

For food, environmental, and pharmaceutical goods to be safe, high-quality, and compliant with regulations, elemental analysis must be precise and trustworthy. In this field, methods like Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) and Neutron Activation Analysis (NAA) are essential. Their use is governed by stringent guidelines and quality frameworks established by international agencies and standardization bodies.

5.1 Use of Neutron Activation Analysis (NAA) in Certified Reference Materials:

A reliable primary analytical method, neutron activation analysis (NAA) is renowned for its high sensitivity, accuracy, and non-destructive character. The characterization of Certified Reference Materials (CRMs), which are crucial for instrument calibration, method validation, and quality control, makes extensive use of it. NAA is used by the International Atomic Energy Agency (IAEA) to certify trace elements in environmental and biological reference materials. It also conducts inter-laboratory comparison studies to harmonize analytical results globally. When high precision is needed, the National Institute of Standards and Technology (NIST) uses NAA to independently verify elemental concentrations in Standard Reference Materials (SRMs). This contributes to the reliability of reference materials used across laboratories worldwide.

5.2 ICP-OES in Routine Laboratory Audits and Food Labeling Compliance:

The multi-element capabilities, speed, and accuracy of Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)

make it a popular tool for regular laboratory analysis. It has two functions in regulatory contexts. In regulatory contexts, its role is twofold. Routine Laboratory Audits: ICP-OES is a preferred tool for monitoring elemental concentrations in water, soil, pharmaceuticals, and food products during internal and external quality audits. Laboratories accredited under ISO/IEC 17025 often adopt ICP-OES for its robust performance and compliance with Good Laboratory Practices (GLP). Food Labeling Compliance: Regulatory bodies require manufacturers to accurately declare nutritional content, including essential minerals (e.g., calcium, iron, magnesium) and to ensure levels of toxic elements (e.g., lead, arsenic) are within permissible limits. ICP-OES enables precise quantification, supporting compliance with national and international food labeling regulations.

5.3 Guidelines from Codex Alimentarius, AOAC, and ISO:

Analytical practices for regulatory compliance are guided by internationally recognized standards and validated methodologies. Codex Alimentarius is developed jointly by FAO and WHO, Codex sets global food standards, including maximum allowable limits for contaminants and nutrients. It also provides performance criteria for analytical methods used in food safety testing. AOAC International publishes Official Methods of Analysis, widely accepted in regulatory and industrial laboratories. These contain elemental analysis protocols that have been validated using ICP-OES, AAS, and other spectrometric techniques, guaranteeing method harmonization and repeatability. The ISO is the International Organization for Standardization. Laboratory competency and technique validation requirements are outlined in ISO standards (such as ISO 17025). ISO also provides specific technical

standards for elemental analysis methods applied in food, water, and environmental testing.

6. FUTURE OUTLOOK

In the field of elemental analysis, selecting the appropriate analytical technique is critical to ensuring data quality, regulatory compliance, and methodological efficiency. Among the most widely utilized tools are Neutron Activation Analysis (NAA) and inductively coupled plasma optical emission spectroscopy (ICP-OES). Each method offers distinct advantages and is subject to specific limitations. Understanding their comparative utility allows laboratories and institutions to make informed decisions based on analytical goals and regulatory requirements.

6.1 Hybrid/Complementary Use:

As analytical requirements become more stringent across environmental, biomedical, nuclear, and materials sciences, hybrid approaches that combine multiple elemental analysis techniques are gaining prominence. Among these, the complementary application of Inductively Coupled Plasma (ICP) techniques, such as ICP-OES and ICP-MS, and Neutron Activation Analysis (NAA) provides increased accuracy, greater confidence, and wider elemental coverage. One of the most reliable applications of NAA is in validating ICP results. NAA is a non-destructive technique known for its matrix independence, high sensitivity (especially for rare earths and halogens), and minimal sample preparation. These characteristics make NAA ideal for confirming results obtained via ICP, particularly when matrix interferences, contamination, or spectral overlaps are a concern. In trace-level determinations such as heavy metals in biological tissues or toxic elements in environmental samples NAA serves as a reference technique, often

uncovering biases or limitations in ICP results stemming from incomplete digestion, ionization interferences, or polyatomic overlaps. Conversely, ICP-MS offers complementary advantages, particularly in terms of sensitivity (down to parts-per-trillion levels), isotopic analysis, and high-throughput quantification of a wide range of elements. Where NAA is limited by its reliance on nuclear facilities and long analysis times, ICP-MS provides rapid, multi elemental capabilities in a compact, lab-based format. In hybrid protocols, ICP-MS is often used as the primary technique for broad screening, with NAA applied selectively for confirmatory analysis or where elements like iodine, arsenic, or thorium are difficult to measure accurately by ICP alone. Together, this hybrid strategy of using NAA to validate ICP-MS or ICP-OES data combines the strengths of both methods: the precision and robustness of NAA with the speed, versatility, and isotopic capabilities of ICP.

6.2 Emerging Trends

Recent advances in analytical chemistry have spurred significant innovations in spectroscopic instrumentation and sample handling, particularly in the realms of Inductively Coupled Plasma (ICP) techniques and Neutron Activation analysis (NAA). Portable ICP instruments are gaining traction due to their compact size, rapid response time, and field applicability. Modern designs integrate miniaturized RF generators, low-argon consumption plasma torches, and solid-state detectors, enabling near real-time multi-elemental analysis in environmental monitoring, mining, and forensic applications. Simultaneously, the search for reactor-free NAA alternatives has intensified due to the limited accessibility of nuclear reactors and increasing regulatory constraints. Accelerator-based methods, such as photon activation analysis (PAA)

and neutron generators using deuterium-tritium fusion, present viable substitutes. These offer safer, scalable, and reactor-independent options while maintaining reasonable sensitivity for trace element quantification. In parallel, there is a marked shift toward green sample preparation for ICP analysis. Traditional digestion methods using strong acids and high temperatures are being replaced by eco-friendlier techniques such as microwave-assisted extraction, ultrasound-assisted digestion, and supercritical fluid extraction. These methods not only reduce reagent use and hazardous waste but also enhance efficiency and analytical precision—key goals in sustainable analytical chemistry. Together, these innovations reflect the broader movement toward portability, safety, and sustainability in elemental analysis.

Future Outlook

The future of elemental analysis lies in both technological innovation and integration of hybrid analytical approaches are gaining traction, combining NAA, ICP-OES, ICP-MS, and XRF to enhance validation, traceability, and confidence in results. Miniaturization and automation are driving developments in ICP-OES, with portable systems and automated sample preparation tools making routine analysis faster and more efficient. Advancements in NAA are focused on improving accessibility, including the development of compact neutron sources and digital detection systems, which may expand its use beyond nuclear facilities. Stricter global regulations and consumer safety concerns are increasing the demand for reliable, trace-level elemental detection across sectors such as food, pharmaceuticals, and environmental science.

In conclusion, both NAA and ICP-OES will continue to play complementary roles in the analytical sciences. While NAA provides

unmatched precision for certain specialized applications, ICP-OES remains a practical and efficient choice for routine compliance and industrial testing. A thoughtful combination of these methods, guided by regulatory standards and technological advancements, will shape the future of high-quality elemental analysis

7. CONCLUSION

The integration of NAA and ICP-OES offers a powerful, complementary approach to elemental analysis, combining the non-destructive accuracy of NAA with the speed and multi element capability of ICP techniques. The choice between them depends on specific needs: NAA excels in complex matrices and trace-level validation, while ICP-OES (and ICP-MS) is ideal for routine, high-through put analysis. Cost, infrastructure, and required sensitivity should guide selection. Laboratories with access to nuclear facilities should leverage NAA for reference and critical validations. ICP-based methods remain the primary tool for rapid screening and industrial applications. Researchers should adopt hybrid strategies where feasible, while policy makers must support access to NAA infrastructure and promote standardization. Together, these approaches ensure robust, accurate, and context-appropriate elemental analysis.

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