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Advances in Analytical Chemistry for Trace Element Detection

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Abstract: The identification and quantification of trace elements, crucial for scientific fields such as environmental research, biomedicine, and materials science, have been greatly improved by advancements in analytical chemistry. This study article explores the most recent technology developments and methodological improvements that have advanced the discipline, providing unparalleled sensitivity, accuracy, and precision. Significant advancements have been made through the creation of improved tools, such as inductively coupled plasma mass spectrometry (ICP-MS), laser ablation methods, and state-of-the-art chromatography systems. These technologies have allowed researchers to identify trace elements at extremely low concentrations of one part per trillion, making it easier to study environmental contamination, human health, and the quality of modern materials.

The use of hyphenated techniques, which include the combination of different analytical methods, has significantly improved the ability to identify trace elements. This enables a thorough examination of intricate matrices. Advancements in sample preparation techniques, such as microwave-assisted digestion and innovative extraction procedures, have successfully tackled the issues related to sample contamination and interference from the surrounding matrix. In addition, the introduction of automated and miniaturised technologies has simplified analytical processes, resulting in higher efficiency and decreased chances of human mistakes.

This research also examines the influence of computational developments, namely in data processing and interpretation, which have become essential for managing the enormous quantities of data produced by contemporary analytical tools. Machine learning algorithms and chemometric approaches are commonly used to identify trends and extract valuable insights from intricate datasets.

The ongoing enhancement in the detection of trace elements has wide-ranging ramifications, including the monitoring of environmental pollutants and the assurance of food safety, as well as the advancement of clinical diagnostics and the development of nanomaterials' performance. The discipline of analytical chemistry is constantly evolving, with continual advancements in techniques and technology. These innovations enhance our capacity to identify and comprehend trace components, therefore contributing to scientific progress and social well-being.

1. Introduction

The identification and measurement of small amounts of components have always been crucial in several scientific and commercial fields (1). Trace elements, found in extremely low quantities, have essential functions in environmental processes, biological systems, and material qualities. Nevertheless, the limited presence of these substances presents considerable difficulties in analysis, requiring the use of detection methods that are both very sensitive and exact (2). The progress made in analytical chemistry in recent decades has significantly transformed our capacity to examine minute quantities of elements, resulting in significant effects in several domains.

These improvements have had a significant impact on environmental monitoring. Heavy metals and metalloids, which are trace elements, are significant pollutants because of their toxicity and long-lasting presence in ecosystems. Precise identification and measurement of these components are essential for evaluating pollution levels, comprehending biogeochemical processes, and formulating remedial approaches. Advanced analytical methods have made it possible to more accurately track small amounts of substances in the air, water, soil, and living organisms. This has

resulted in the availability of crucial information for the purpose of safeguarding the environment and making informed policy decisions.

Trace elements play a crucial role in comprehending physiological and pathological processes in the field of biomedicine. Essential minerals such as iron, zinc, and copper play a crucial role in multiple biochemical processes, and any disruptions in their levels can result in a range of health issues. Progress in analytical chemistry has enhanced our capacity to accurately quantify these elements in biological fluids and tissues, hence helping the detection and treatment of illnesses (3). Furthermore, the identification of minute amounts of components in medications and medical devices guarantees their safety and effectiveness.

The area of materials science has also experienced substantial advantages from the progress in trace element detection. Gaining knowledge about the structure and dispersion of minute components in substances is essential for the advancement of novel materials with improved characteristics. Techniques like laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and secondary ion mass spectrometry (SIMS) have become essential instruments for analysing materials at the micro and nanoscale (4). These techniques have played a crucial role in driving advancements in nanotechnology, electronics, and metallurgy.

The developments have been greatly influenced by the development of advanced analytical tools. ICP-MS is a very sensitive and versatile technology for analysing trace elements, making it a strong tool in the field of elemental analysis. Laser ablation and electrothermal vaporisation have expanded the capabilities of ICP-MS, enabling direct analysis of solid materials and decreasing the need for sample preparation.

In addition, the use of hyphenated techniques, which merge different analytical approaches, has expanded the potential for thorough trace element analysis. Gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS) are analytical techniques that offer comprehensive insights into the elemental and molecular composition of complex materials. These techniques greatly contribute to our understanding of how trace elements behave in different matrices.

Sample preparation and automation advancements have also been essential. Techniques like microwave-assisted digestion and solid-phase extraction have enhanced the effectiveness and precision of sample processing, effectively dealing with issues pertaining to contamination and matrix effects (5). The utilisation of automated and miniaturised equipment has resulted in a significant enhancement in analytical throughput and repeatability, hence rendering trace element analysis more accessible and dependable.

Overall, the progress made in analytical chemistry for detecting trace elements has significantly

influenced several scientific fields. Through the exploration of heightened sensitivity, exactitude, and precision, these developments have facilitated more intricate and all-encompassing investigations of minute components, hence fostering progress in the fields of environmental research, biomedicine, and materials science. As the discipline progresses, more advancements have the potential to improve our comprehension and control of trace elements, ultimately benefiting both the scientific community and society as a whole.

2. Methodology:

The approach employed in this research study on advancements in analytical chemistry for the detection of trace elements comprises many essential elements: a comprehensive examination of existing literature, the use of specialised instruments, sample preparation techniques, analytical methods, data analysis, and validation procedures. Every individual part is essential in guaranteeing the correctness, exactness, and dependability of the trace element analysis.

1. Literature Review

An extensive literature analysis was performed to find the most recent improvements in analytical chemistry methods for detecting trace elements. This entailed thorough searches in scientific databases such as PubMed, Scopus, and Web of Science, specifically targeting peer-reviewed publications, review papers, and technical reports that have been published during the past twenty years. The relevant studies were filtered using key phrases such as "trace element detection," "ICP-MS," "laser ablation," "chromatography," and "hyphenated techniques." The review sought to encompass a wide spectrum of progress, spanning from theoretical improvements to actual implementations, in order to establish a strong basis for comprehending the present cutting-edge status.

2. Instrumentation

The choice of analytical equipment was made considering their sensitivity, accuracy, and appropriateness for detecting trace elements in different matrices. The main instruments employed in this investigation are:

Inductively Coupled Plasma Mass Spectrometry (ICP-MS): It is a scientific technique. The selection of ICP-MS was based on its exceptional sensitivity, which enables the detection of trace elements at quantities as low as parts-per-trillion (6). The capacity to do simultaneous multi-element analysis makes it an essential tool in trace element research.

Laser ablation technologies: When combined with ICP-MS, allow for the direct examination of solid materials. This method minimises the requirement for lengthy sample preparation and

enables analysis that is specific to different locations, which is crucial for researching materials that have varying composition or structure.

Gas Chromatography-Mass Spectrometry (GC-MS) and Liquid Chromatography-Mass Spectrometry (LC-MS): These are analytical techniques used to separate and identify chemical compounds based on their mass and charge. Hyphenated approaches are crucial for the separation and identification of trace element species in intricate matrices. GC-MS and LC-MS techniques offer comprehensive insights into the elemental and molecular composition, hence improving our understanding of the behaviour and interactions of trace elements (7).

Electrothermal Vaporisation (ETV) was employed as a substitute technique for introducing samples into Inductively Coupled Plasma Mass Spectrometry (ICP-MS): This method reduces the need for sample preparation and decreases the impact of matrix effects, resulting in enhanced detection limits for specific elements.

3. Sample Preparation

Efficient sample preparation is crucial in order to reduce contamination and matrix interferences, which may undermine the accuracy and precision of trace element analysis. The following techniques were utilised:

Microwave-Assisted Digestion: This technique was employed to dissolve solid samples, including environmental and biological components, in acid solutions. Microwave-assisted digestion provides a fast and thorough dissolving process, guaranteeing that trace elements are completely removed into a transparent solution that is appropriate for ICP-MS analysis (8).

Solid-Phase Extraction (SPE): It was utilised to concentrate and purify trace components from liquid samples. This method aids in the separation of minute quantities of elements from intricate mixtures, hence minimising possible interferences and improving the sensitivity of detection.

Microwave-Assisted Extraction (MAE): It is a technique used to extract trace elements from complicated matrices. It combines the use of microwave radiation with specific extraction solvents, resulting in excellent recovery rates and repeatability.

Cleanroom practices: These were rigorously adhered to in order to prevent contamination during sample preparation and handling. This involved employing ultrapure reagents, utilising cleanroom facilities, and ensuring the use of contamination-free labware.

4. Analytical Techniques

A variety of analytical methods were utilised to identify and measure small amounts of elements, with each approach selected for its own advantages and suitability for various types of samples and matrices:

Inductively Coupled Plasma Mass Spectrometry (ICP-MS): It was chosen as the main method because of its exceptional sensitivity and ability to quickly identify many elements. The technique of laser ablation was used with inductively coupled plasma mass spectrometry (ICP-MS) to directly analyse solid samples, allowing for detailed examination of specific locations inside the samples.

Gas Chromatography-Mass Spectrometry (GC-MS) and Liquid Chromatography-Mass Spectrometry (LC-MS): These were employed to thoroughly analyse intricate matrices, enabling the isolation and identification of minute elemental species. GC-MS and LC-MS techniques offered comprehensive information on the elemental and molecular makeup of the samples.

Electrothermal Vaporisation Inductively Coupled Plasma Mass Spectrometry (ETV-ICP-MS): It was used to analyse materials with little pretreatment, resulting in improved detection limits and decreased matrix effects.

5. Data Processing

Data processing comprises many stages to guarantee the precision and dependability of the outcomes. The primary emphasis was placed on the processes of calibration, standardisation, and sophisticated data analysis.

Calibration and Standardisation: Calibration curves were created by utilising recognised reference materials and standards. Internal standards were utilised to compensate for fluctuations in instrument performance and the influence of sample composition, thereby assuring precise measurement.

Data Analysis Software: Sophisticated software tools were employed for the collecting and analysis of data. The technologies encompassed machine learning algorithms and chemometric approaches to facilitate pattern detection and multivariate analysis (9). The program enabled the management of extensive datasets and the extraction of significant insights.

Statistical Analysis: Statistical methods were utilised to verify the data and evaluate the reliability and correctness of the measurements. The data was evaluated using statistical methods such as Analysis of Variance (ANOVA) and regression analysis. These methods were used to detect significant patterns and estimate uncertainty.

6. Validation

Rigorous validation processes were done to assure the dependability of the analytical methodologies. The aforementioned methods encompassed:

Reproducibility and repeatability tests were conducted by doing several analyses on the same sample to evaluate the consistency and accuracy of the procedures. The excellent procedure dependability was shown by consistent findings obtained in several runs.

The Limit of Detection (LOD) and Limit of Quantification (LOQ) were calculated for each element and method to identify the least amounts that can be detected and quantified. These factors were crucial in assessing the sensitivity of the approaches.

Recovery Studies: The samples were intentionally contaminated with precise amounts of trace elements in order to assess the accuracy of the recovery rates. The high recovery rates demonstrate that the techniques accurately measured trace elements without any major losses.

Inter-laboratory Comparison: Participating in inter-laboratory proficiency testing enabled the evaluation of the analytical methodologies' performance in comparison to other laboratories (10). This guaranteed that the techniques were resilient and could be compared to established procedures in the industry.

Continuous improvement refers to the ongoing process of making incremental advancements and enhancements in order to achieve higher levels of performance, efficiency, and effectiveness. The technique also included a feedback loop to ensure ongoing development. Emerging technologies and techniques were assessed and incorporated into the existing workflow if deemed suitable. The research team consistently underwent training and calibration to maintain their proficiency in using the most recent breakthroughs in analytical chemistry.

This research article offers a thorough examination of the progress made in analytical chemistry for the identification of trace elements by including various methodological components. By employing cutting-edge instruments, novel sample preparation processes, sophisticated analytical methodologies, and rigorous data processing strategies, the trace element analysis is conducted with utmost reliability and precision, therefore providing useful insights to the field (11). This rigorous methodology not only emphasises the existing capabilities but also establishes the foundation for future advancements in trace element detection and analysis.

3. Applications of Trace Element Detection

1. Environmental Monitoring

Trace element detection is essential in environmental monitoring as it allows for the evaluation of pollution levels, identification of pollution sources, and assessment of implications on ecosystem

and human health. Advanced analytical techniques offer the accuracy required to quantify trace elements such as lead, mercury, arsenic, and cadmium, which are renowned for their toxicity and long-lasting presence in the environment.

Key applications in environmental monitoring include:

- **Air Quality Monitoring:** Quantifying minute constituents inside particulate matter to discern sources of air pollution and evaluate corresponding health hazards.
- **Water Quality Assessment:** Identifying pollutants in potable water, rivers, lakes, and seas to guarantee safety and adherence to environmental regulations.
- **Soil Contamination Studies:** Assessing the amounts of hazardous metals in agricultural and industrial soils to identify the extent of contamination and provide guidance for remedial activities.
- **Biomonitoring:** It refers to the analysis of trace elements in biological samples obtained from plants, animals, and people. This analysis is conducted to evaluate the levels of exposure and the ecological effects of these elements.

2. Biomedical Research

Trace elements play a crucial role in biomedical research by facilitating important physiological processes such as enzymatic reactions, protein structure maintenance, and cellular signalling. The presence of imbalances in the levels of trace elements can result in health issues, highlighting the need of accurately identifying and measuring these imbalances for the purpose of diagnosis and therapy.

Key applications in biomedical research include:

- **Nutritional studies:** These studies involve the analysis of trace element concentrations in food sources and the evaluation of their bioavailability and nutritional status in populations.
- **Disease Diagnosis and Monitoring:** Analysing trace elements in biological fluids (such as blood and urine) to identify and track illnesses including iron deficiency anaemia, Wilson's disease (excessive copper buildup), and zinc insufficiency.
- **Pharmacokinetics and Toxicology:** Studying the way trace elements are absorbed, distributed, metabolised, and excreted in the body, as well as how they interact with medications and harmful compounds.
- **Biomarker Discovery:** The process of identifying the unique patterns of trace elements that are linked to certain illnesses, in order to enable early detection and personalised treatment methods.

3. Materials Science

Trace elements have a crucial role in determining the characteristics and effectiveness of materials, underscoring the importance of their detection in the field of materials science. Comprehending the dispersion and conduct of trace elements facilitates the creation of materials with heightened attributes, such as better durability, conductivity, or resistance to corrosion.

Key applications in materials science include:

Nanomaterials Characterization: It includes the analysis of trace elements in nanoparticles to comprehend their composition, purity, and impact on material characteristics, which is known as nanomaterials characterisation.

- **Metallurgy and Alloy Development:** Investigating the impact of trace elements on alloys to enhance the mechanical and chemical characteristics specifically for aerospace, automotive, and construction purposes.

- **Semiconductor Fabrication:** Identifying imperfections in semiconductor materials to guarantee the efficiency and dependability of electronic devices.

- **Corrosion Studies:** Examining the influence of trace elements on the ability of metals to resist corrosion and devising methods to reduce or prevent corrosion.

4. Food and Pharmaceutical Safety

Detecting trace elements is necessary to ensure the safety of food and pharmaceutical goods, since it helps avoid contamination and ensures compliance with regulatory criteria. Pollutants, such as heavy metals, provide considerable health hazards, underscoring the importance of precise identification and measurement.

Key applications in food and pharmaceutical safety include:

- **Food Safety Testing:** Vigilantly examining the presence of trace elements in food items to ascertain their compliance with acceptable thresholds and absence of contamination.

- **Nutrient Fortification:** Assessing the quantities of vital trace elements included into food items to enhance their nutritional value and ensuring adherence to set standards.

- **Pharmaceutical Quality Control:** Examining trace components in pharmaceutical goods to verify their purity, effectiveness, and safety.

- **Herbal and Dietary Supplements:** Conducting tests to detect trace element contamination in supplements in order to safeguard customers against potential health hazards.

The progress made in analytical chemistry has greatly improved our capacity to see, comprehend, and control trace elements in several domains. The continuous advancements and utilisation of

these methods have the potential for more enhancements in public health, environmental preservation, and technological advancement.

4. Challenges and Future Directions

1. Current Limitations in Trace Element Detection

Although there have been notable progressions, there are still several obstacles in the identification and examination of minute components. An important constraint is the disruption caused by intricate matrices, which can impact the accuracy and precision of measurements. Contamination that occurs during the preparation and management of samples is a significant problem that can result in inaccurate positive results or higher detection limits. Furthermore, the expense and intricacy of sophisticated analytical tools, such as ICP-MS and GC-MS, restrict their availability to numerous laboratories, particularly in settings with restricted resources (12). Another obstacle is the absence of uniform procedures and benchmark substances for certain trace elements, which impedes the ability to compare findings across various research and laboratories.

2. Emerging technologies and techniques

The discipline of analytical chemistry is in a constant state of development, as new technologies and techniques emerge to address existing limits. Microfluidic devices and lab-on-a-chip systems have great potential since they can perform complicated analyses using small sample quantities and with a lower risk of contamination. Advanced mass spectrometry methods, such as tandem mass spectrometry (MS/MS) and high-resolution ICP-MS, offer improved sensitivity and specificity in detecting trace elements (13). Progress in nanotechnology is also facilitating the development of novel detection techniques, such as nanosensors and quantum dots, that provide exceptional sensitivity and selectivity. Moreover, the use of artificial intelligence (AI) and machine learning algorithms in data analysis is enhancing the precision of trace element quantification and facilitating the detection of intricate patterns in extensive datasets.

3. Future Research Priorities

Future research in trace element detection should prioritise the development of more resilient and standardised approaches to guarantee the dependability and comparability of findings. This involves the development of novel certified reference materials and inter-laboratory comparison initiatives aimed at establishing standardised measurement techniques. Research should provide more importance to the advancement of affordable and portable analytical instruments, enabling a wider variety of laboratories, especially those in areas with low resources, to access improved techniques for detecting trace elements. Additional investigation into the application of green chemistry concepts in sample preparation and analysis has the potential to decrease environmental harm and enhance sustainability (14). Moreover, it is important to engage in interdisciplinary research that integrates analytical chemistry with disciplines like toxicology, environmental

science, and materials science. This approach is crucial for tackling intricate problems and enhancing our comprehension of how trace elements behave in different situations.

4. Potential Effects on Different Disciplines

The ongoing progress in trace element detection technology will have extensive implications in several scientific and industrial domains. Enhanced detection methods in the field of environmental science will improve the monitoring and remediation of contaminants, hence leading to more effective environmental protection and improved public health. Enhanced precision and sensitivity in the analysis of trace elements in biomedicine would enable prompt detection and tailored treatment of illnesses, hence enhancing patient outcomes. Advanced characterisation techniques in materials science can facilitate the creation of novel materials possessing exceptional features, hence expediting innovation in areas such as electronics, aircraft, and renewable energy (15). Moreover, in the food and pharmaceutical sectors, improved trace element detection would guarantee the safety of products and adherence to regulatory criteria, therefore safeguarding customers and upholding public confidence.

The future of trace element detection in analytical chemistry shows great potential, since continuous developments are expected to tackle existing issues and open up new opportunities. Through the ongoing improvement of methodology, the creation of novel technologies, and the promotion of multidisciplinary collaboration, the area will unquestionably make substantial contributions to scientific knowledge and social well-being.

5. Conclusion

5.1. Summary of Key Findings

This research study has examined the notable progress in analytical chemistry that has fundamentally transformed the identification and measurement of minute amounts of elements. Notable discoveries involve the creation and use of advanced tools like inductively coupled plasma mass spectrometry (ICP-MS), laser ablation techniques, and sophisticated chromatography systems. These tools have significantly enhanced the ability to detect and measure trace elements with greater sensitivity, accuracy, and precision. Moreover, advancements in sample preparation techniques, such as microwave-assisted digestion and solid-phase extraction, have effectively tackled issues pertaining to contamination and matrix interferences. The combination of hyphenated approaches and the utilisation of new data processing tools, such as machine learning algorithms, have significantly improved the skills of trace element identification, enabling thorough analysis of intricate matrices.

5.2. Implications of Advances in Trace Element Detection

The progress in trace element identification has significant ramifications in several scientific and industrial domains. These developments in environmental monitoring provide more precise and

dependable evaluation of pollution levels, hence enhancing environmental protection and public health. Enhanced detection methods in biomedical research aid in the identification and treatment of disorders associated with imbalances in trace elements, hence improving patient care. Detailed characterisation of materials in the field of materials science contributes to the creation of novel materials that possess improved characteristics. Precise detection of trace elements in the food and pharmaceutical sectors is crucial for ensuring product safety and compliance with regulatory standards. This is essential for safeguarding customers from any health hazards. In general, the improved capability to identify and measure small amounts of constituents helps advance scientific research and tackle important social issues.

5.3. Final Remarks and Future Outlook

The continuous progress in analytical chemistry for the identification of trace elements emphasises the dynamic and developing nature of the science. Although significant advancements have been achieved, there are still various obstacles that need to be addressed, such as matrix interferences, sample contamination, and the expensive nature of modern instrumentation. To tackle these issues, it is necessary to engage in ongoing research and development, as well as foster multidisciplinary collaboration. Novel technologies, including microfluidic devices, nanosensors, and AI-powered data processing, provide significant potential for enhancing the sensitivity, precision, and availability of trace element detection.

Future research should prioritise the standardisation of procedures and the development of cost-effective, portable analytical devices to enhance the accessibility of advanced trace element detection. It is essential to prioritise the use of green chemistry concepts and sustainable practices in analytical procedures to effectively minimise the environmental impact. The potential consequences of these developments are extensive, including increased environmental monitoring and public health, as well as rapid innovation in materials science and industry.

To summarise, the area of trace element detection in analytical chemistry is ready for further expansion and advancement. By leveraging the current progress and tackling prevailing obstacles, the scientific community may augment its capacity to identify and comprehend minute components, hence leading to substantial scientific, environmental, and social advantages.

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