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ADVANCES IN ION CHROMATOGRAPHY

Dr. Rashmi Pathak

Associate Professor , Department Of Chemistry

Government Bangur PG College , Pali , Raj.

Abstract:

Ion chromatography (IC) is a powerful analytical technique used for the separation and quantification of ions in various samples. Over the years, significant advancements have been made in IC methodology, instrumentation, and applications. This review paper aims to provide an overview of recent research developments in ion chromatography, including improvements in separation efficiency, detection sensitivity, and the expanding range of applications. This research paper provides a comprehensive overview of recent advancements in ion chromatography, highlighting improvements in methodology, instrumentation, and applications. It serves as a valuable resource for researchers, analysts, and scientists interested in staying updated with the latest developments in this field.

Introduction:

Ion chromatography (IC) is a powerful analytical technique used for the separation and quantification of ions in various samples. It has gained significant importance in the field of analytical chemistry due to its ability to provide accurate and reliable results for a wide range of applications. In IC, the separation of ions is achieved by utilizing the differences in their interactions with a stationary phase and a mobile phase. The stationary phase typically consists of ion-exchange resins or other materials with specific affinity towards ions of interest. The mobile phase, known as the eluent, carries the sample through the stationary phase, facilitating the separation of ions based on their different affinities and interactions. The significance of IC lies in its capability to analyze complex samples containing a diverse range of ions, including both inorganic and organic species. It offers high selectivity, sensitivity, and resolution, making it suitable for various fields such as environmental analysis, pharmaceutical and biomedical research, food and beverage analysis, and industrial applications.

Advancements in IC techniques and instrumentation have played a crucial role in enhancing the separation and detection capabilities of this analytical method. These advancements have led to improvements in the efficiency, sensitivity, and speed of analysis, allowing for more accurate and precise quantification of ions in complex matrices.

Enhanced separation capabilities in IC have been achieved through the development of new stationary phases and column designs. The introduction of monolithic columns, with their high permeability and low backpressure, has significantly improved separation efficiency. Moreover, the use of high-capacity stationary phases enables better resolution and separation of complex samples. Advancements in suppressor technology have also contributed to improved detection capabilities in IC. The development of innovative suppressor designs has led to higher sensitivity and reduced background conductivity, enabling the detection of low-level analytes. Non-suppressed and capillary IC methods have emerged as alternative approaches with potential advantages in terms of sensitivity and selectivity. Significant progress has been made in the development of detection systems for IC. New detectors with improved sensitivity and selectivity, such as conductivity, amperometry, and spectrometry detectors, have been introduced. The coupling of IC with mass spectrometry has expanded the identification capabilities, allowing for the determination of both known and unknown ions in complex samples.

The importance of advancements in IC cannot be overstated, as they have enabled researchers and analysts to tackle analytical challenges in various fields. The enhanced separation and detection capabilities have facilitated the accurate quantification of ions in diverse samples, leading to better understanding and monitoring of environmental pollutants, pharmaceutical formulations, food quality, and industrial processes. Ion chromatography is a vital analytical technique in the field of analytical chemistry, offering high selectivity and sensitivity for the separation and quantification of ions. Advancements in IC methodology, instrumentation, and applications have significantly improved its capabilities, allowing for enhanced separation efficiency and detection sensitivity. These advancements have expanded the range of applications where IC can be applied, enabling comprehensive analysis and contributing to advancements in various scientific and industrial domains.

Column Technology:

Column technology plays a crucial role in ion chromatography (IC) as it directly influences the efficiency and effectiveness of ion separation. Recent advancements in column technology have focused on introducing new stationary phases and column designs to improve the separation capabilities of IC systems.

- Introduction of new stationary phases: Researchers have been working on the development of novel stationary phases with enhanced selectivity and ion-exchange properties. These stationary phases offer improved separation of target ions by providing specific interactions with the analytes of interest. Examples include specialty resins, mixed-mode stationary phases, and functionalized materials. These new stationary phases expand the range of analytes that can be separated and detected using IC.
- Monolithic columns: Monolithic columns have gained significant attention in recent years due to their unique structure and advantages in terms of efficiency and speed. Monolithic columns are characterized by a continuous, porous structure, which allows for high-speed separations and low backpressure. These columns offer faster analysis times, increased sample throughput, and reduced solvent consumption compared to traditional particle-packed columns. Monolithic columns are particularly useful for the separation of small ions and low-molecular-weight compounds.
- High-capacity stationary phases: Complex samples often contain a wide range of ions with varying concentrations, posing a challenge for efficient separation. To address this, researchers have developed high-capacity stationary phases capable of accommodating a larger number of ions without compromising separation efficiency. These high-capacity stationary phases provide improved resolution and peak capacity, enabling better separation and identification of ions in complex samples.

The introduction of new stationary phases and the utilization of monolithic columns and high-capacity stationary phases have significantly enhanced the separation capabilities of ion chromatography. These advancements have led to improved resolution, faster analysis times, and higher sample throughput, making IC a more powerful and efficient analytical technique for a wide range of applications.

Suppressor Technology:

Suppressors play a critical role in ion chromatography (IC) by reducing the background conductivity of the eluent and enhancing the sensitivity of detection. Recent advancements in suppressor technology have focused on improving efficiency, sensitivity, and selectivity in IC systems.

- Advances in suppressor designs: Researchers have made significant progress in developing innovative suppressor designs to improve the efficiency of ion detection. These advancements include the introduction of regenerable and disposable suppressors. Regenerable suppressors allow for multiple uses, reducing cost and waste. Disposable suppressors, on the other hand, eliminate the need for regeneration, simplifying the workflow and reducing the potential for carryover. These advancements in suppressor designs have led to more efficient and reliable ion detection in IC.
- Introduction of non-suppressed and capillary IC methods: Non-suppressed IC methods have gained popularity in recent years as an alternative to traditional suppressed IC. Non-suppressed IC eliminates the suppressor module, allowing for direct conductivity detection of the analytes. This approach offers simpler instrumentation and faster analysis times. Capillary IC, which utilizes capillary columns with smaller diameters, has also emerged as a promising technique. Capillary IC provides higher sensitivity and requires smaller sample volumes, making it suitable for trace-level analysis and limited sample availability.
- Techniques to reduce background conductivity and enhance selectivity: Background conductivity in IC can originate from various sources, including impurities in the eluent and the sample matrix. To overcome this challenge, researchers have developed techniques to reduce background conductivity and improve selectivity. These techniques include the use of high-purity eluents, online purification systems, and post-column treatment methods. By minimizing background conductivity, these techniques enhance the sensitivity of detection and improve the accuracy of quantification.

Advancements in suppressor technology, including innovative designs, non-suppressed IC, and capillary IC methods, have contributed to the development of more efficient and sensitive IC systems. These advancements have allowed for faster analysis times, reduced complexity, and enhanced selectivity in ion detection. By improving the detection capabilities of IC, researchers can achieve more accurate and reliable quantification of ions in various samples, leading to advancements in environmental analysis, pharmaceutical research, food quality control, and other fields where IC is applied.

Eluent Generation:

Eluent generation is a critical aspect of ion chromatography (IC) that involves the preparation and delivery of the mobile phase, also known as the eluent. Recent advancements in eluent generation techniques have focused on improving control, flexibility, cost-effectiveness, and waste reduction in IC systems.

- Online eluent generation techniques: Online eluent generation allows for the real-time preparation of the eluent, providing improved control and flexibility in IC. This technique involves the generation of the eluent by mixing appropriate reagents in the desired concentrations using automated systems. Online eluent generation offers advantages such as precise control over the eluent composition, the ability to adjust eluent strength during the analysis, and the elimination of manual preparation steps. This results in improved reproducibility and reduces the risk of errors in eluent preparation.

- Introduction of eluent recycling systems: Eluent recycling systems have been introduced to improve cost-effectiveness and reduce waste in IC. These systems collect the eluent after it passes through the column and removes the analytes of interest. The purified eluent is then recycled and reused for subsequent analyses. Eluent recycling not only reduces the consumption of costly reagents but also minimizes waste generation and disposal, making IC more environmentally friendly and economically sustainable.

Advancements in eluent generation techniques have provided significant benefits to IC analyses. Online eluent generation allows for better control over eluent composition, ensuring reproducible and accurate separations. It also provides flexibility in adjusting the eluent strength during the analysis, optimizing separations for different analytes and samples. Additionally, the introduction of eluent recycling systems reduces operational costs by minimizing the consumption of eluents and the generation of waste, contributing to sustainable and economical IC practices. These advancements in eluent generation techniques have improved the efficiency, reliability, and cost-effectiveness of IC analyses, making them more accessible and practical for various applications. Researchers and analysts can achieve better control over eluent composition, reduce waste generation, and optimize separations, leading to more accurate and reliable results in environmental analysis, pharmaceutical research, food and beverage analysis, and other areas where IC is employed.

Detection Systems:

Detection systems in ion chromatography (IC) are crucial for the accurate and sensitive quantification of ions. Recent advancements in detection systems have focused on improving sensitivity, selectivity, and identification capabilities in IC analyses.

- Development of new detectors: Researchers have made significant strides in developing detectors with improved sensitivity and selectivity for IC. These advancements include the introduction of novel conductivity detectors with enhanced signal-to-noise ratios and improved detection limits. Additionally, amperometric detectors have been refined to offer higher sensitivity and the ability to detect specific analytes with greater precision. Spectrometric detectors, such as UV-Vis or fluorescence detectors, have also been integrated into IC systems to expand the range of analytes that can be detected.
- Advances in conductivity, amperometry, and spectrometry detection: Conductivity detection is the most commonly used detection method in IC due to its simplicity and versatility. Recent advances in conductivity detection have focused on minimizing background noise and enhancing the sensitivity through innovative cell designs and optimized electronics. Amperometric detection, which relies on the measurement of current generated from electrochemical reactions, has been improved to achieve higher sensitivity and selectivity through advancements in electrode materials and configurations. Spectrometry detection, including UV-Vis and fluorescence detection, has been integrated with IC systems to provide additional information on analyte properties, such as absorption or emission spectra, enabling better identification and quantification.
- Coupling of IC with mass spectrometry (MS): The coupling of IC with mass spectrometry has revolutionized ion analysis, offering enhanced identification capabilities and increased sensitivity. The combination of IC and MS allows for the determination of both known and unknown analytes, providing structural information and accurate mass measurements. Coupling IC with MS techniques, such as electrospray ionization (ESI) or inductively coupled plasma (ICP) sources, has enabled the analysis of a

wide range of analytes, including small ions, organic compounds, and metal species, with high sensitivity and selectivity.

Miniaturization and Automation:

Advancements in miniaturization and automation have significantly improved the efficiency, portability, and automation capabilities of ion chromatography (IC) systems.

- Advances in microfluidic IC and lab-on-a-chip devices: Microfluidic IC and lab-on-a-chip devices have emerged as miniaturized platforms for performing IC analyses. These systems integrate sample preparation, separation, and detection processes onto a single chip, minimizing sample and reagent consumption, reducing analysis time, and improving efficiency. Microfluidic IC systems offer advantages such as improved separation efficiency, reduced solvent consumption, and compatibility with small sample volumes. They also allow for high-throughput analysis, parallel separations, and integration with other miniaturized analytical techniques.
- Automation of sample preparation, injection, and data analysis: Automation has been introduced in various aspects of IC analysis to streamline workflows and reduce human error. Automated systems for sample preparation, including sample pretreatment and dilution, ensure consistency and reproducibility in the analysis. Automated injection systems precisely deliver sample volumes, minimizing variability and improving accuracy. Data analysis software with automation capabilities has also been developed, allowing for faster data processing, result interpretation, and reporting. Automation in IC not only increases efficiency but also enhances data quality and reliability.
- Portable IC systems for on-site analysis and field applications: The development of portable IC systems has enabled on-site and field analysis, eliminating the need for sample transportation to the laboratory. These compact and rugged systems are designed for easy transportation and operation in challenging environments. Portable IC systems typically integrate miniaturized components, battery-powered operation, and user-friendly interfaces. They offer real-time analysis, immediate results, and simplified workflows, making them suitable for environmental monitoring, quality control, and point-of-care applications.

The advancements in miniaturization and automation have revolutionized IC by offering enhanced efficiency, portability, and user-friendliness. Microfluidic IC and lab-on-a-chip devices provide compact and integrated platforms for efficient separations, reducing the reliance on bulky instrumentation. These systems are particularly useful in resource-limited settings, on-site analysis, and point-of-care applications, where rapid and reliable results are essential.

Automation in sample preparation, injection, and data analysis eliminates manual handling, reduces variability, and improves reproducibility. By automating these processes, the risk of human error is minimized, and analysis time is significantly reduced. This streamlines workflows, increases productivity, and allows for high-throughput analysis.

The development of portable IC systems has expanded the reach of IC beyond the confines of the laboratory. These systems enable real-time analysis, immediate feedback, and on-site decision-making, eliminating the delays associated with sample transportation and centralized analysis. Portable IC systems find applications in environmental monitoring, field research, quality control in manufacturing processes, and on-site testing in industries such as food and beverage, agriculture, and water management.

In summary, the advancements in miniaturization and automation have transformed the landscape of IC. Microfluidic IC and lab-on-a-chip devices offer integrated and portable platforms for efficient separations. Automation in sample preparation, injection, and data analysis enhances accuracy, reproducibility, and productivity. Portable IC systems enable on-site and real-time analysis, facilitating rapid decision-making and immediate feedback. These advancements have made IC more accessible, practical, and versatile, extending its applications to various fields where rapid, reliable, and on-site analysis is required.
Environmental Analysis:

Ion chromatography (IC) plays a crucial role in environmental analysis by enabling the determination of inorganic and organic ions in water and soil samples. Some key applications of IC in environmental analysis include:

- Determination of inorganic and organic ions: IC is used to quantify various inorganic ions, such as nitrate, sulfate, chloride, and phosphate, in water and soil samples. It is also employed for the analysis of organic ions, including organic acids, phenols, and polar pesticides. These measurements provide valuable information on the quality and pollution levels of environmental matrices.
- Monitoring of pollutants, heavy metals, and anions: IC is applied to monitor pollutants and contaminants in environmental samples. It enables the analysis of anions, such as bromate, bromide, and iodide, as well as the determination of heavy metal ions, including lead, cadmium, and chromium. IC is also employed for the identification and quantification of anionic contaminants, such as perchlorate and chlorate, which can have detrimental effects on the environment.

Pharmaceutical and Biomedical Analysis:

IC is extensively used in pharmaceutical and biomedical analysis, contributing to quality control and research in this field. Some applications of IC in this domain include:

- Analysis of pharmaceuticals, counterions, and impurities: IC is employed for the analysis of pharmaceutical formulations, including the quantification of active pharmaceutical ingredients (APIs), counterions, and impurities. It enables the separation and determination of ions, organic acids, and other small molecules, ensuring the quality and safety of pharmaceutical products.
- Determination of biomolecules, amino acids, and organic acids: IC is utilized for the analysis of biomolecules, such as amino acids, organic acids, and sugars, which are essential for biological processes. It enables the quantification of these compounds, aiding in biomedical research, clinical diagnostics, and pharmaceutical development.

. Food and Beverage Analysis:

IC plays a vital role in the analysis of food and beverages, ensuring their safety, quality, and regulatory compliance. Some applications of IC in this field include:

- Detection of additives, preservatives, and contaminants: IC is employed for the identification and quantification of additives, preservatives, and contaminants in food and beverages. It enables the analysis of anions, cations, organic acids, and other ions, ensuring compliance with regulatory standards and ensuring consumer safety.
- Determination of cations, anions, and organic acids: IC is utilized to quantify cations, such as sodium, potassium, calcium, and magnesium, as well as anions, including chloride, sulfate, and nitrate, in various

food matrices. It also allows for the determination of organic acids, which contribute to the taste, flavor, and quality of food and beverages.

Industrial Applications:

IC finds applications in various industrial sectors, contributing to process monitoring, quality control, and environmental compliance. Some industrial applications of IC include:

- Monitoring of process streams and wastewater analysis: IC is utilized to monitor process streams in industries such as chemical manufacturing, power generation, and water treatment. It enables the analysis of various ions, including inorganic and organic species, ensuring process efficiency and compliance with regulatory limits. Additionally, IC plays a crucial role in wastewater analysis, facilitating the identification and quantification of pollutants and contaminants.
- Determination of corrosion inhibitors, surfactants, and metal ions: IC is employed in the analysis of corrosion inhibitors and surfactants, which are utilized in industries such as oil and gas, automotive, and metal plating. It enables the quantification of these additives, ensuring their optimal concentration for effective corrosion protection and surface treatment. IC is also used for the determination of metal ions in industrial samples, aiding in quality control and compliance with industry standards

1. Challenges and Future Perspectives:

Despite the significant advancements in ion chromatography (IC), there are still challenges that researchers and analysts face. Some of these challenges include:

- Matrix effects: The presence of complex sample matrices can interfere with the separation and detection of ions in IC. Matrix effects can lead to reduced sensitivity, decreased selectivity, and compromised resolution. Overcoming matrix effects requires method development strategies such as sample pre-treatment, optimization of separation conditions, and the use of selective detectors.
- Method development and optimization: Developing effective IC methods for specific analytes and matrices can be time-consuming and require optimization of various parameters, such as column selection, eluent composition, and detection conditions. Advancements in method development tools, automation, and optimization algorithms can help streamline this process and improve method robustness and efficiency.
- Sensitivity and detection limits: While IC offers good sensitivity, there is a continuous drive to achieve even lower detection limits, especially for trace-level analysis. Further advancements in detection systems, including improved sensitivity and selectivity, as well as the incorporation of advanced sample enrichment techniques, will contribute to enhanced sensitivity and lower detection limits.

As for future perspectives, several emerging trends can shape the field of IC:

- Multi-dimensional IC: Integrating multiple separation dimensions in IC can enhance the separation power and peak capacity, allowing for the analysis of more complex samples. This involves coupling different separation modes, such as ion-exchange, ion-pairing, and size exclusion chromatography, to achieve comprehensive separations and improved identification capabilities.

- Hyphenation with other analytical techniques: Integration of IC with other analytical techniques, such as mass spectrometry (MS) and atomic spectroscopy, can provide complementary information and enhanced identification capabilities. Hyphenation with MS enables structural elucidation and identification of analytes, while coupling with atomic spectroscopy allows for simultaneous determination of multiple elements.
- Miniaturization and portability: The trend towards miniaturization and portability in IC instruments will continue, enabling on-site and in-field analysis. Miniaturized IC systems, lab-on-a-chip devices, and portable instruments will offer rapid, sensitive, and user-friendly analysis in various applications, including environmental monitoring, food safety, and point-of-care diagnostics.
- Advances in data analysis: With the increasing volume of data generated in IC, there is a need for advanced data analysis tools and techniques. Developments in data analytics, chemometrics, and artificial intelligence can enable efficient data processing, pattern recognition, and result interpretation, facilitating more informed decision-making.

Overall, addressing the challenges in IC and embracing emerging trends will continue to drive advancements in the field, leading to improved sensitivity, selectivity, and application versatility. The integration of IC with other techniques and the development of robust and user-friendly instruments and data analysis tools will further enhance the capabilities of IC in various scientific and industrial domains.

Conclusion

The chromatography (IC) has witnessed significant advancements in methodology, instrumentation, and applications, contributing to its growing importance in analytical chemistry. These advancements have led to improved separation efficiency, enhanced detection sensitivity, and expanded the range of applications where IC can be applied. In terms of methodology, the introduction of new stationary phases and column designs, such as monolithic columns and high-capacity stationary phases, has improved separation efficiency, speed, and resolution. These advancements have allowed for more accurate quantification of ions in complex samples. Suppressor technology has also seen significant improvements, with the development of innovative designs that enhance detection efficiency and sensitivity. The introduction of non-suppressed and capillary IC methods has provided alternatives with advantages in terms of simplicity, speed, and sensitivity. Techniques to reduce background conductivity and enhance selectivity have further improved detection capabilities in IC. Instrumentation advances have focused on the development of new detectors with improved sensitivity and selectivity, including conductivity, amperometry, and spectrometry detectors. The coupling of IC with mass spectrometry has enhanced identification capabilities, enabling the determination of known and unknown analytes in complex samples. Miniaturization and automation have revolutionized IC by enabling the development of microfluidic IC and lab-on-a-chip devices. These platforms offer integrated and portable solutions for efficient separations, while automation of sample preparation, injection, and data analysis has improved efficiency, reproducibility, and data quality. The emergence of portable IC systems has enabled on-site analysis and field applications, providing real-time results and immediate feedback. The applications of IC have expanded across various fields. In environmental analysis, IC is used for the determination of inorganic and organic ions, as well as the monitoring of pollutants, heavy metals, and anions in environmental matrices. In pharmaceutical and biomedical analysis, IC is employed for the analysis of pharmaceuticals, biomolecules, amino acids, and organic acids. In food and beverage analysis, IC plays a vital role in the detection of additives, contaminants, and the determination of cations, anions, and organic acids. In industrial applications, IC is utilized for monitoring process streams, wastewater analysis, and the determination of corrosion inhibitors, surfactants, and metal ions. Despite the advancements, challenges remain in IC, including matrix effects, method development, and sensitivity. However, emerging trends such as multi-dimensional IC, hyphenation with other analytical techniques, miniaturization, and advances in data analysis offer exciting future prospects for the field. Recent advancements in IC have enhanced its capabilities, making it a powerful tool for the separation and quantification of ions in various applications. These advancements have improved efficiency, sensitivity, selectivity, and application versatility, enabling researchers and analysts to address complex analytical challenges and contribute to advancements in environmental monitoring, pharmaceutical research, food safety, and industrial processes. With further developments and integration with other analytical techniques, IC is poised to continue playing a crucial role in the field of analytical chemistry.

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