

# A New Era of Chromatographic Technology: Integration and Application of Intelligent, Automated, and Green Analytical Methods

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## ABSTRACT

Chromatographic technology, as a vital tool in modern analytical chemistry, is widely applied in fields such as environmental monitoring, food safety, and pharmaceutical testing. With the advancement of artificial intelligence (AI) and the promotion of green development concepts, chromatographic technology is progressively evolving towards intelligence, automation, and sustainability. Intelligence enhances analytical precision and efficiency, automation meets the demands for high-throughput detection, and sustainability drives forward environmentally-friendly practices. This paper, considering China's national context, explores the forefront developments and application challenges of chromatographic technology, proposing strategies to foster technological innovation and industrialization, thereby supporting global green development.

## KEYWORDS

Chromatographic technology; intelligence; automation; sustainability; green development

## 1 Introduction

Since its inception in the early 20th century, chromatographic technology has become a core tool in modern analytical chemistry, with widespread applications in environmental monitoring, food safety, pharmaceutical testing, and life sciences. <sup>[1]</sup>Driven by the advancement of artificial intelligence (AI), big data, and green development concepts, chromatographic technology is undergoing profound transformations. Intelligent chromatography, through machine learning and data optimization, achieves automation and efficient processing, significantly enhancing analytical precision and speed. Automated chromatography, by enabling efficient sample handling and real-time control, provides large-scale industrial testing solutions. Green chromatography, by reducing solvent usage and lowering energy consumption, promotes the sustainability of the analytical process in response to global environmental demands. In China, the integration of intelligent, automated, and green chromatography technologies presents both opportunities and challenges for technological innovation.

Intelligence and automation have become key trends in the global development of chromatographic technology, particularly with the advancement of artificial intelligence and deep learning, which have significantly improved the efficiency and reliability of automated chromatographic analysis. However, issues such as cost, system integration, and sustainability remain bottlenecks in technological development. In particular, in China, the ability to promote localized research and development, enhance system adaptability, and break through technological bottlenecks will determine the future of chromatographic technology. The integration of intelligent and green technologies in chromatography aligns with China's "14th Five-Year Plan" strategy on scientific innovation and green development, driving the green transformation of both the environmental protection industry and traditional industries. This paper will analyze the current state and trends of chromatographic technology both globally and in China, explore how intelligence, automation, and sustainability are shaping China's innovation advantage, and propose corresponding technological, industrial, and policy recommendations to promote the long-term development of chromatographic technology.

## 2 Basic Theory and Current Development of Chromatographic Technology

### 2.1 Basics and Classification of Chromatographic Technology

Chromatographic technology is a method for separation and analysis based on the differences in the distribution of substances between a stationary phase and a mobile phase. It is widely used in fields such as environmental monitoring, food testing, and pharmaceutical analysis. The basic principle is to achieve separation by the differing migration rates of various components of the sample between different phases. Common chromatographic techniques include gas chromatography (GC), high-performance liquid chromatography (HPLC), and capillary electrophoresis (CE), each of which has distinct advantages depending on the sample and analytical requirements. <sup>[2]</sup> Gas chromatography is suitable for gas sample analysis, liquid chromatography is widely used for the separation of liquids or dissolved substances, and capillary electrophoresis, with its high resolution and low sample requirements, shows strong advantages in the analysis of

biological macromolecules.

Driven by the concept of green development, the emerging supercritical fluid chromatography (SFC) technology, due to its lower solvent demands, has become an ideal choice for green analysis. Additionally, the combined gas-liquid technologies (GC-MS, LC-MS) are increasingly applied in environmental monitoring, drug analysis, and other fields. Despite significant progress in these technologies, challenges such as solvent consumption and complex operations persist, highlighting the urgent need for innovative solutions and technological breakthroughs.

## **2.2 The Rise and Development of Intelligent Chromatographic Technology**

Intelligent chromatographic technology, relying on AI and machine learning (ML) algorithms, enables automatic optimization, data processing, and result analysis, significantly improving the efficiency and precision of chromatographic techniques. The core advantage lies in using big data and algorithmic optimization of the chromatographic separation process, reducing human intervention and operational errors, thus improving analytical accuracy and reliability. For example, machine learning can automatically adjust separation conditions and optimize experimental parameters, reducing experimental errors and shortening analysis time. However, intelligent chromatographic technology faces challenges such as the universality of algorithms, insufficient system integration, and issues with data acquisition quality control. Furthermore, the high cost of intelligent systems and their reliance on high-quality data limit their adoption in small and medium-sized laboratories and industrial applications. Nevertheless, with advances in technology and the development of data science, intelligent chromatographic technology is undoubtedly becoming a key direction for the future of chromatographic analysis.

## **2.3 The Concept and Practice of Green Chromatographic Technology**

The core concept of green chromatographic technology is to reduce reliance on harmful solvents, lower energy consumption, and improve analytical efficiency, thereby promoting environmental protection and sustainable development. The emergence of new environmentally-friendly separation media and green solvents has made the greening of chromatographic technology possible. For example, the use of water-based solvents and supercritical carbon dioxide as green solvents has significantly reduced the use of organic solvents, helping to reduce the environmental impact of the analytical process. Supercritical fluid chromatography (SFC), with its superior solvating power and lower energy consumption, has become an important breakthrough in green chromatographic technology, particularly showing great potential in environmental monitoring and food safety. However, the high cost of green solvents and the technological and industrial challenges of replacing traditional solvents on a large scale remain issues. With the promotion of green policies and the maturation of technology, green chromatographic technology will increasingly be applied and become an important driver of sustainable development in analytical chemistry.

# **3 Innovation and Application of Intelligent Chromatographic Technology**

## **3.1 Application of Artificial Intelligence in Chromatographic Analysis**

AI, particularly machine learning (ML) and data mining technologies, has become a key tool for enhancing the efficiency and accuracy of chromatographic analysis. Through data prediction and pattern recognition, machine learning can process large volumes of complex data, automatically identify important features in chromatograms, such as peak shapes and retention times, and optimize the separation process. The continuous optimization of AI algorithms enables the chromatographic separation process to be automatically adjusted, not only improving analysis efficiency but also reducing human intervention and minimizing the risk of operational errors.

AI-based chromatographic separation optimization and automated operation have become important directions for the innovation of chromatographic instruments. AI can analyze experimental data in real time and automatically adjust separation conditions (such as flow rate, temperature, solvent ratio, etc.) to achieve optimal separation results. Additionally, intelligent chromatographs, with self-diagnosis and fault warning functions, can automatically identify and resolve faults, significantly improving equipment stability and maintenance efficiency. These intelligent devices greatly enhance the convenience and efficiency of large-scale sample analysis in industrial applications, such as pharmaceutical quality control and environmental monitoring, showing broad application prospects.

## **3.2 Innovation of Intelligent Chromatographic Instruments and Equipment**

High-throughput automated chromatographic systems are a significant result of the development of intelligent chromatographic technology in recent years. By integrating advanced sensors, automated sample injection systems, and

data processing platforms, these systems can perform efficient analysis of large volumes of samples without human intervention. <sup>[3]</sup>Such systems not only significantly improve analytical efficiency but also increase the stability and repeatability of analysis results, making them particularly suitable for high-throughput scenarios such as clinical drug analysis, environmental monitoring, and food safety testing. Meanwhile, intelligent control systems with online analysis and real-time data feedback provide essential support for real-time adjustments during the experimental process, further enhancing data accuracy and processing speed.

The market prospects for intelligent chromatographic instruments are extremely broad, but technical bottlenecks still exist. Currently, high-throughput automated systems need improvements in integration, flexibility, and cost control, particularly in terms of adaptability across different application fields. Moreover, the development of intelligent chromatographic instruments faces challenges in data storage, processing speed, and algorithm optimization. Nonetheless, with the continuous advancement of AI technologies and the gradual reduction of costs, intelligent chromatographic instruments are expected to be more widely applied in industries such as healthcare, environmental protection, and pharmaceuticals in the future.

### 3.3 Intelligent Chromatographic Data Processing and Analysis

One of the core values of intelligent chromatographic technology is the automation and real-time analysis of data processing. Through advanced data acquisition systems, intelligent chromatographs can automatically record and analyze experimental data, real-time calculation of parameters such as peak area and concentration, and avoid errors in manual processing. Progress in data management and algorithm optimization, particularly in noise reduction and signal-to-noise ratio improvement, makes chromatographic data more accurate and reliable. At the same time, intelligent analysis systems can automatically detect anomalies and provide optimization suggestions, significantly improving experimental efficiency and the reliability of results. The integration of AI and big data technologies makes data processing and interpretation more precise and efficient. By analyzing historical data through machine learning models, the system can quickly extract key information and perform trend predictions and pattern recognition. This not only enables high-throughput, high-precision chromatographic analysis but also provides new opportunities for personalized sample analysis. For instance, in drug development, AI-optimized chromatographic analysis can significantly shorten analysis cycles and improve R&D efficiency. With the continuous advancement of data acquisition and processing technologies, the accuracy and speed of intelligent chromatographic data analysis will further improve, driving industry development.

## 4 Current Status and Challenges of Automated Chromatographic Analysis Technology

### 4.1 Design and Application of Automated Chromatographic Systems

Automated chromatographic experimental systems achieve full-process automation of chromatographic analysis by integrating sample injection, separation, detection, and data analysis. The basic principle is to automate traditional manual operations by coordinating the work of components such as robotic arms, automatic samplers, and flow control systems, thereby improving the efficiency and accuracy of experiments. In industrial production and pharmaceutical testing, the application of automated chromatography has become an important tool for quality control and process optimization. For instance, in the pharmaceutical industry, automated chromatographic systems can efficiently analyze raw materials, products, and intermediates, ensuring stability and compliance during the production process. Automated chromatography is particularly advantageous in large-scale sample analysis. Traditional chromatographic analysis usually requires manual intervention, which limits its use in high-volume sample processing. Automated systems, designed for high throughput, can handle large numbers of samples simultaneously, providing more consistent and accurate results.

<sup>[4]</sup>This technology not only improves work efficiency but also effectively reduces human error, offering reliable technical support for large-scale pharmaceutical monitoring, environmental monitoring, and other fields.

### 4.2 Optimization and Technological Advancements in Automated Chromatographic Operations

Optimizing sample preparation and analysis workflows in automated chromatographic systems is key to improving system performance. In traditional chromatography, sample preparation steps such as extraction and concentration often require manual operations, which are time-consuming and prone to error. In automated systems, integrated sample processing modules enable seamless transition from sample preparation to analysis, significantly improving efficiency and accuracy. Recent advancements in automated sample preparation technologies, such as online filtration and automated liquid-solid extraction, have made chromatographic analysis more efficient and precise. To enhance resolution and sensitivity, automated separation systems have continuously improved in areas such as column design, mobile phase

selection, and detector optimization. For example, optimizing the size and packing material of the separation column and improving the mobile phase ratio can effectively increase analytical resolution. Additionally, the use of more advanced detectors, such as high-sensitivity mass spectrometry (MS) and ultraviolet (UV) detectors, has greatly enhanced sensitivity. However, the bottleneck for automated chromatographic systems remains the high cost of equipment, inadequate handling of complex samples, and system stability. In the future, a balance between technological innovation and economic feasibility needs to be achieved.

### 4.3 Practical Application Cases of Automated Chromatographic Technology

Automated chromatographic technology has made significant advancements in environmental monitoring, especially in air and water quality monitoring. Automated chromatographic systems can analyze pollutant components in the environment in real-time under continuous operating conditions, ensuring the accuracy and timeliness of data. In air quality monitoring, automated systems integrate online sampling and detection functions, enabling real-time monitoring of pollutant concentrations and providing high-precision separation results. In water quality monitoring, automated chromatographic technology effectively analyzes trace organic pollutants in water, helping environmental protection agencies respond promptly and take necessary remedial actions. In food and pharmaceutical quality testing, automated chromatographic technology has also played an important role. In the field of food safety, automated chromatographic systems can efficiently detect pesticide residues, additives, and other substances in food, ensuring consumer safety. For pharmaceutical quality testing, automated chromatography technology can efficiently analyze raw materials, intermediates, and finished products during production, ensuring that the drugs meet quality standards and preventing the entry of counterfeit or substandard drugs into the market.<sup>[5]</sup>

## 5 Innovation and Application of Green Chromatographic Technology

### 5.1 Development of Green Chromatographic Materials and Separation Media

The research and development of green chromatographic materials mainly aims to reduce the negative environmental impact of chromatographic analysis, particularly by developing eco-friendly fillers and hydrophilic materials to replace traditional harmful solvents and materials. For example, in recent years, silica-based alternatives and non-toxic, biodegradable polymer materials have gained widespread attention. Hydrophilic separation media not only reduce the use of organic solvents but also enhance analytical efficiency and decrease waste emissions. The development of these new materials not only meets environmental protection requirements but also improves the sustainability of chromatographic analysis. The standards for selecting green separation media are continually being refined, covering aspects such as the availability of raw materials, energy consumption during production, and the recyclability of the final material.

### 5.2 Optimization and Application of Green Chromatographic Methods

One major innovation in green chromatographic technology is the substitution of solvents and the use of micro-solvents. By selecting green solvents, such as water, ethanol, and carbon dioxide, which are environmentally friendly, the environmental burden can be significantly reduced. The criteria for selecting solvents not only focus on their environmental friendliness but also ensure their separation efficacy and cost-effectiveness in chromatographic analysis. The use of micro-solvents reduces solvent consumption and waste liquid handling, enhances experimental efficiency, and lowers costs. This method has been widely applied in environmental monitoring, pharmaceuticals, and food analysis. Supercritical fluid chromatography (SFC) and micro-chromatography are key areas for optimizing green chromatographic methods.<sup>[6]</sup> SFC uses supercritical carbon dioxide instead of traditional organic solvents, lowering energy consumption and reducing the use of organic solvents. This technique is suitable for the efficient separation of both polar and non-polar compounds. Meanwhile, micro-chromatography, which uses miniaturized devices and analytical columns, reduces solvent usage and operation time, further advancing green practices. Green chromatographic technology has been particularly successful in food and environmental monitoring. For example, in water quality monitoring, green chromatographic techniques can precisely detect trace organic pollutants in water while reducing environmental contamination.<sup>[7]</sup>

### 5.3 Challenges and Future Trends of Green Chromatographic Technology

Although green chromatographic technology has made significant progress, its global promotion and implementation still face several challenges.<sup>[8]</sup> First, the standardization of green chromatographic methods needs to be addressed,

particularly as regulations and technical standards have not been unified across different countries and regions, creating barriers to the widespread adoption of green chromatographic technology. Furthermore, due to the generally higher costs of eco-friendly materials and green solvents, many companies face significant financial pressure when selecting green technologies, limiting their widespread application. In the future, the development of green chromatographic technology will continue to focus on integrating environmental protection, low cost, and high efficiency. As technology advances, new green chromatographic separation media and solvents will be developed to achieve higher analytical performance while ensuring environmental sustainability. Additionally, the industrialization of green technologies will gradually accelerate, especially in developing countries such as China. Green chromatographic technology is expected to drive industry transformation and upgrading through policy support and technological innovation. In the coming years, green chromatographic technology will not only become an important trend in global laboratory analysis but will also play an increasingly significant role in environmental protection, energy conservation, and other fields.

## 6 Conclusion

Chromatographic technology has undergone a profound transformation, evolving from traditional separation and analysis to intelligent, automated, and green methods, gradually becoming a core tool in modern analytical chemistry. Intelligent chromatography, through the application of artificial intelligence (AI) and machine learning, has enhanced analytical accuracy and efficiency. Automated chromatography, by enabling high-throughput processing and real-time control, meets the demand for large-scale detection. Green chromatography, relying on environmentally friendly materials and energy-efficient methods, promotes sustainable development. These technological innovations have advanced global progress in the field of analysis and provided strong support for China's green development and technological innovation. However, despite the significant progress made, chromatographic technology still faces challenges such as cost, system integration, and standardization. As technology matures and policy support strengthens, chromatographic technology is expected to see broader applications in areas such as environmental protection, healthcare, and food safety, further facilitating the green transition and sustainable development.

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