

Advances in Analytical Chemistry Research Methodology: Trends and Applications

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Abstract

Analytical chemistry is critical to scientific study because it allows for the accurate identification, measurement, and characterization of chemical compounds. Recent advances in methodology have improved accuracy, sensitivity, and efficiency, with techniques such as High-Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), Mass Spectrometry (MS), and Nuclear Magnetic Resonance (NMR) spectroscopy transforming analytical procedures. The combination of Artificial Intelligence (AI) and Machine Learning (ML) has enhanced data processing, pattern recognition, and automation while reducing human error and increasing reproducibility. Green analytical chemistry is gaining importance, promoting sustainable practices such as solvent reduction, eco-friendly reagents, and miniaturized techniques to reduce environmental impact. Additionally, microfluidic and lab-on-a-chip technologies enable real-time, portable, and high-throughput analysis, benefiting pharmaceuticals, environmental monitoring, food safety, and forensic science. Despite these advancements, challenges like standardization, cost, and instrumentation complexity persist. This paper explores recent trends in analytical chemistry, emphasizing technological innovations, applications, and future prospects of this rapidly evolving field.

Keywords: Analytical chemistry, chromatography, spectroscopy, artificial intelligence, green chemistry

INTRODUCTION

Analytical chemistry is a key discipline that allows for the identification, quantification, and characterization of chemical molecules in a variety of domains, including medicines, environmental science, and forensics [1]. Over the last few decades, advances in analytical techniques have greatly increased the precision, sensitivity, and efficiency of chemical analysis. High-performance techniques such as High-Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), Mass Spectrometry (MS), and Nuclear Magnetic Resonance (NMR) spectroscopy have revolutionized the way chemical substances are studied [2].

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The use of Artificial Intelligence (AI) and Machine Learning (ML) in analytical chemistry has improved data processing capabilities, allowing for advanced pattern identification, automation, and error reduction [3]. These technologies help with real-time monitoring, predictive modeling, and the optimization of experimental protocols. AI-powered analytical tools have been very useful in drug development, environmental monitoring, and sophisticated biochemical research [4].

Green analytical chemistry has arisen as a sustainable method for lowering the environmental

impact of chemical analysis. This includes reducing solvent consumption, using environmentally friendly reagents, and implementing miniaturized techniques like microfluidic and lab-on-a-chip systems [5]. These solutions not only help to ensure sustainability, but they also improve analytical process efficiency by allowing for rapid, high-throughput analysis [6].

Despite these advances, difficulties such as high apparatus costs, analytical technique complexity, and the requirement for standardization continue to be key considerations [7]. Researchers are constantly attempting to improve the price, accessibility, and repeatability of analytical procedures so that they can be used in a variety of businesses. Addressing these difficulties will necessitate collaboration among scientists, regulatory organizations, and industry players [8].

This study examines the most recent trends in analytical chemistry, concentrating on technological advancements, applications, and future prospects. It highlights the impact of AI, green chemistry, and microfluidic technologies, as well as the problems that must be solved to assure the field's continuing evolution [9]. Figure 1 shows a structured representation of these developments and their relationships.

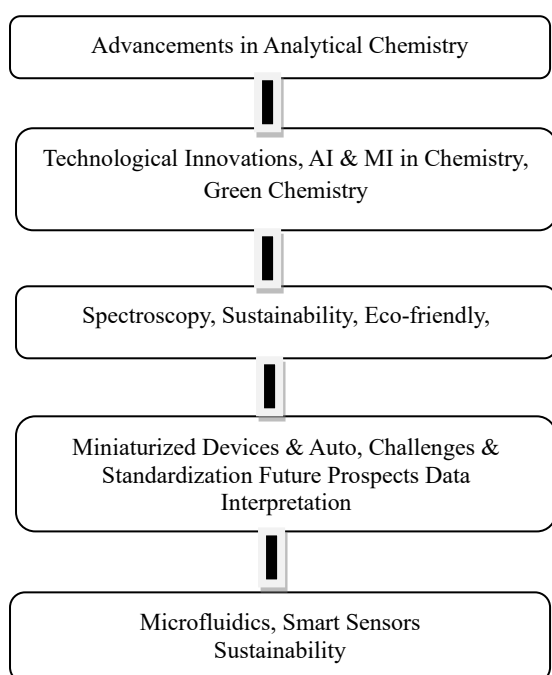


Figure 1. Advancements in Analytical Chemistry: Trends, Technologies, and Challenges

Recent advances in analytical chemistry have resulted in the development of increasingly sophisticated procedures, allowing researchers to detect tiny amounts of chemicals with unparalleled precision. For example, ultrahigh-performance liquid chromatography (UHPLC) and tandem mass spectrometry (MS/MS) have enhanced the detection of medications, poisons, and pollutants in complex biological and environmental materials [10]. Furthermore, advances in spectroscopy, such as Raman and infrared (IR) spectroscopy, have improved non-destructive analysis techniques, allowing for real-time monitoring and quick identification of chemical substances [11]. These approaches are widely used in food safety, forensic science, and clinical diagnostics [12].

The incorporation of smaller analytical equipment, such as microfluidics and lab-on-a-chip technologies, has revolutionized chemical analysis by reducing sample volume, reagent use, and enabling portable and real-time analysis [13]. These technologies are especially useful for point-of-care diagnostics, environmental monitoring, and biomedical research [14]. Furthermore, the use of automation and robotics in analytical laboratories has improved efficiency and reproducibility while

reducing human intervention and mistake [15]. These developments help to meet the increased demand for high-throughput screening techniques in drug discovery and biochemical research.

As analytical chemistry evolves, addressing difficulties such as data interpretation, apparatus cost, and technique standardization is critical. Large datasets are rapidly generated, necessitating improved computational tools for reliable interpretation and decision-making [16]. Furthermore, regulatory compliance and quality assurance methods are critical for assuring the dependability and repeatability of analytical techniques in industries like pharmaceuticals and environmental science [17]. Future research should prioritize enhancing analytical chemistry's accessibility, affordability, and sustainability in order to broaden its impact across a wide range of scientific and industrial applications [18].

RELATED WORKS

The field of analytical chemistry has witnessed significant advancements, with numerous studies focusing on the development and refinement of analytical techniques, AI integration, and sustainable methodologies. Several key contributions to the field are discussed below.

Advances in Chromatographic and Spectroscopic Techniques

Recent research has highlighted the increasing precision and efficiency of chromatographic and spectroscopic techniques. Studies on ultrahigh-performance liquid chromatography (UHPLC) and tandem mass spectrometry (MS/MS) have demonstrated their capability in detecting trace levels of pharmaceutical compounds, contaminants, and toxic substances in biological and environmental samples [10]. Additionally, Raman and infrared (IR) spectroscopy have been explored for their potential in non-destructive and real-time analysis, benefiting food safety, forensic science, and medical diagnostics [11, 12].

Artificial Intelligence and Machine Learning in Analytical Chemistry

The application of AI and ML in analytical chemistry has been extensively studied, particularly in automating data analysis, optimizing experimental conditions, and enhancing pattern recognition. Research has shown that AI-driven methods can improve peak detection in chromatographic techniques, reduce noise in spectroscopic analysis, and enable real-time monitoring of chemical processes [3, 4]. Furthermore, deep learning models have been employed for spectral interpretation, facilitating rapid identification of chemical compounds with improved accuracy [16]. AI has also played a crucial role in predictive modeling for drug development and environmental pollution monitoring [17].

Green Analytical Chemistry and Sustainability

The principles of green chemistry have been increasingly integrated into analytical methodologies to reduce environmental impact. Studies have emphasized the benefits of solvent reduction, eco-friendly reagent use, and energy-efficient instrumentation [5]. Miniaturized techniques, including microfluidics and lab-on-a-chip technologies, have been extensively investigated for their potential in decreasing sample and reagent consumption while maintaining analytical precision [6, 18]. These methods have found applications in point-of-care diagnostics, environmental testing, and biochemical analysis, promoting sustainability in chemical research [18].

Microfluidic and Lab-on-a-Chip Technologies

Microfluidic and lab-on-a-chip systems have emerged as transformative tools in analytical chemistry, offering portable, high-throughput, and real-time analytical solutions. Studies have demonstrated their efficacy in biomedical applications, including disease detection, personalized medicine, and rapid pathogen identification [13, 14]. The development of integrated sensor technologies has further enhanced the capabilities of these systems, allowing for precise control of fluid dynamics and reaction kinetics in microscale environments [8]. Researchers continue to refine these technologies for improved sensitivity, reproducibility, and affordability [7].

Challenges in Analytical Chemistry and Future Directions

Despite the rapid progress in analytical techniques, challenges such as standardization, data interpretation, and instrumentation costs persist. Several studies have addressed the need for harmonized protocols and quality assurance measures to ensure reproducibility across different laboratories [9]. Advances in chemometric tools and computational algorithms have been explored to handle large datasets efficiently, aiding in complex data interpretation [15]. Additionally, research has focused on developing cost-effective and accessible analytical tools to expand their applicability in resource-limited settings [2].

The continuous evolution of analytical chemistry demands ongoing research efforts to overcome existing limitations and leverage emerging technologies for improved chemical analysis. Future studies should aim to integrate AI-driven automation, enhance sustainability practices, and develop user-friendly analytical platforms for broader industrial and scientific applications [1].

CHROMATOGRAPHY TECHNIQUES

Chromatography is a fundamental tool in analytical chemistry, used to separate, identify, and quantify complicated chemical mixtures. Advanced chromatographic techniques, including High-Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), Ultrahigh-Performance Liquid Chromatography (UHPLC), and Tandem Mass Spectrometry (MS/MS), have greatly enhanced analytical precision, sensitivity, and efficiency [1]. These methods are commonly utilized in pharmaceutical research, environmental monitoring, food safety, and forensic science.

High-Performance Liquid Chromatography (HPLC)

HPLC is a valuable analytical method for separating and measuring chemicals in complicated mixtures. It works on the basis of differential partitioning between a mobile and stationary phase, resulting in great resolution and reproducibility [2]. Recent advancements in HPLC include ultra-fast liquid chromatography (UFLC) and column miniaturization, which enhance efficiency and reduce solvent consumption [3]. The development of green HPLC methods, such as the use of eco-friendly solvents and biodegradable stationary phases, has further minimized environmental impact [4]. Applications of HPLC range from pharmaceutical drug analysis to biomarker identification in clinical research [5].

Gas Chromatography (GC)

GC is primarily used for the analysis of volatile and semi-volatile compounds. It relies on the partitioning of analytes between a gas mobile phase and a solid or liquid stationary phase [6]. The introduction of advanced detectors, such as flame ionization detectors (FID) and mass spectrometry detectors (GC-MS), has greatly improved the sensitivity and specificity of GC methods [7]. Furthermore, fast GC and multidimensional GC (GC×GC) techniques have enhanced the resolution and throughput of analyses [8]. GC is extensively applied in environmental monitoring, forensic toxicology, and petrochemical industries [9].

Ultrahigh-Performance Liquid Chromatography (UHPLC)

UHPLC is an evolution of HPLC that employs smaller particle-size columns (<2 μm) and operates at higher pressures (>6000 psi), leading to faster separations with superior resolution [10], refer Figure 2, also refer the table 1. Compared to conventional HPLC, UHPLC offers reduced analysis time, lower solvent consumption, and enhanced peak resolution, making it a preferred choice for high-throughput laboratories [11]. Coupling UHPLC with mass spectrometry (UHPLC-MS) has further improved its capability in metabolomics, proteomics, and pharmaceutical quality control [12]. The application of AI-driven automation in UHPLC systems has streamlined data analysis and increased reproducibility in research laboratories [13].

Table 1. Comparison of UHPLC and HPLC.

Parameter	UHPLC	HPLC
Particle Size	<2 μm	3–5 μm
Operating Pressure	>6000 psi (up to 15,000 psi)	Up to 6000 psi
Analysis Time	Shorter (higher efficiency)	Longer
Solvent Consumption	Lower (cost-effective)	Higher
Peak Resolution	Higher (better separation of compounds)	Lower
Sensitivity	Higher	Moderate
Coupling with MS	Common (UHPLC-MS)	Less frequent
Automation & AI	AI-driven automation enhances reproducibility	Less integration of AI

Figure 2. Comparison of Analysis time and Peak resolution

Tandem Mass Spectrometry (MS/MS)

Tandem mass spectrometry (MS/MS) is a sophisticated analytical technique that uses multiple mass analyzers to achieve excellent specificity and structural elucidation of substances [14]. When combined with chromatographic techniques like HPLC or GC, MS/MS allows for highly sensitive identification of trace-level analytes [15]. Advances in ionization techniques, such as electrospray ionization (ESI) and matrix-assisted laser desorption/ionization (MALDI), have broadened MS/MS applications in proteomics, metabolomics, and environmental science (16). Additionally, real-time MS/MS analysis using ambient ionization methods has facilitated rapid screening in forensic and clinical diagnostics [17]. AI-driven data processing algorithms have further enhanced the interpretation of complex MS/MS spectra, reducing human error and improving analytical accuracy [18]. Figure 3.

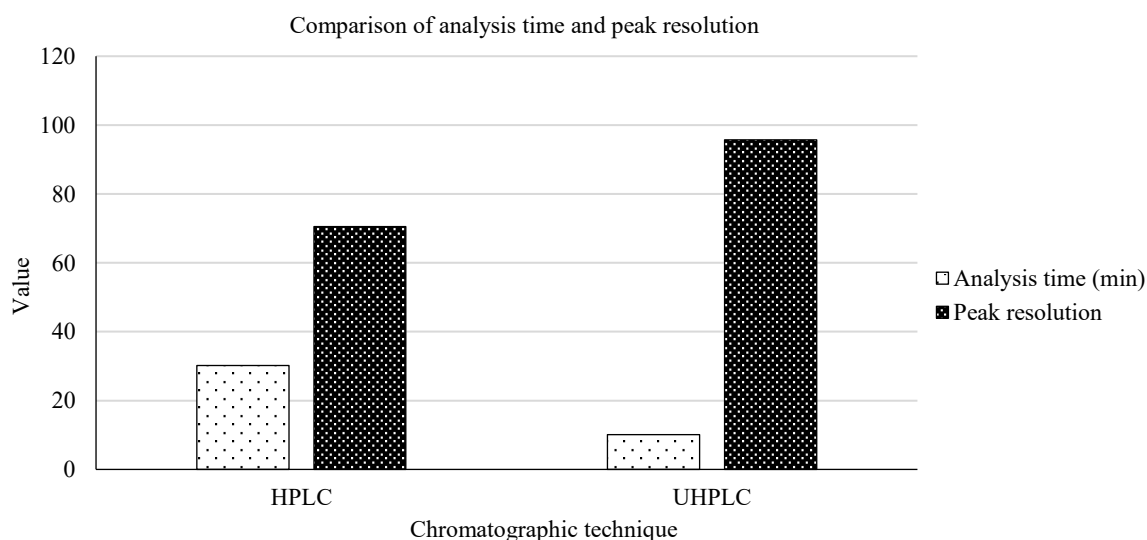


Figure 3. Comparison of Analysis Time and Peak resolution.

SPECTROSCOPY METHODS

Spectroscopy techniques are essential analytical tools used for the identification, structural elucidation, and quantitative analysis of chemical compounds. Advances in Mass Spectrometry (MS), Nuclear Magnetic Resonance (NMR) spectroscopy, and Infrared (IR) and Raman spectroscopy have significantly improved accuracy, sensitivity, and reproducibility in various scientific domains [1].

Mass Spectrometry (MS)

Mass Spectrometry (MS) is a powerful technique that allows the determination of molecular weight, structure, and composition of chemical compounds. It works by ionizing sample molecules and

analyzing their mass-to-charge ratios (m/z) [2]. MS is widely used in pharmaceutical analysis, metabolomics, and proteomics due to its high sensitivity and precision [3]. The combination of MS with chromatography techniques such as GC-MS and LC-MS enhances separation and detection capabilities [4]. Advanced Tandem Mass Spectrometry (MS/MS) enables further fragmentation of ions for structural elucidation, making it an indispensable tool in forensic, environmental, and biomedical research [5].

Nuclear Magnetic Resonance (NMR) Spectroscopy

NMR spectroscopy is a non-destructive analytical technique for studying molecular structures, dynamics, and interactions. It is based on the interaction of atomic nuclei with an external magnetic field, which produces distinct resonance signals that aid in identifying functional groups and molecular conformations [6]. High-Resolution NMR (HR-NMR) and Solid-State NMR provide enhanced resolution for complex biological and chemical systems [7]. In pharmaceutical research, NMR is used for drug purity analysis, metabolomics, and biomarker discovery [8]. Furthermore, the integration of AI-driven spectral interpretation has improved data processing and accuracy in structural assignments [9].

Infrared (IR) and Raman Spectroscopy

NMR spectroIR and Raman spectroscopy are vibrational spectroscopic techniques for molecular fingerprinting that detect typical functional group vibrations. Fourier Transform Infrared (FTIR) spectroscopy is widely used for identifying organic and inorganic compounds based on their absorption of infrared light at specific wavelengths [10]. Raman spectroscopy, in contrast, measures inelastic scattering of monochromatic light, offering complementary molecular information [11]. These techniques are valuable for material characterization, food safety analysis, and forensic investigations [12]. Surface-Enhanced Raman Spectroscopy (SERS) has further expanded Raman applications by increasing sensitivity for trace-level detection in biosensing and medical diagnostics [13].

ARTIFICIAL INTELLIGENCE & MACHINE LEARNING IN ANALYTICAL CHEMISTRY

The application of Artificial Intelligence (AI) and Machine Learning (ML) to analytical chemistry has considerably improved the accuracy, efficiency, and automation of complicated data-driven operations. AI-driven approaches facilitate automated data processing, pattern recognition, chemometrics, and advanced instrumentation control, leading to improvements in precision and reproducibility in analytical workflows [1].

Automated Data Processing

Analytical chemistry generates vast datasets from techniques such as chromatography, spectroscopy, and mass spectrometry. Traditional techniques of data interpretation frequently necessitate significant manual involvement, making them susceptible to human mistake. AI-driven automated data processing allows for rapid and accurate extraction of meaningful insights from complex datasets [2]. Deep learning algorithms improve spectral deconvolution, peak detection, and noise reduction in analytical measurements [3]. Additionally, AI-based predictive models aid in estimating unknown compound properties, optimizing experimental conditions, and reducing time-consuming manual analyses [4].

Pattern Recognition and Chemometrics

AI-powered pattern recognition techniques are widely used in chemometrics, a field that applies statistical and mathematical models to extract relevant chemical information from experimental data [5]. Machine learning algorithms, such as Principal Component Analysis (PCA), Support Vector Machines (SVM), and Artificial Neural Networks (ANNs), allow for classification, clustering, and quantitative predictions in complicated analytical research [6]. In pharmaceutical quality control and environmental monitoring, chemometric models assist in differentiating between chemically similar compounds, detecting impurities, and predicting physicochemical properties based on spectral or chromatographic patterns [7]. AI-enhanced chemometrics also plays a crucial role in food safety, forensic science, and metabolomics, ensuring rapid and accurate identification of chemical substances [8].

AI-driven Instrumentation Control

The integration of AI in analytical instrumentation has led to the development of self-optimizing and autonomous systems that minimize manual intervention and enhance operational efficiency [9]. AI-driven robotic automation in high-throughput laboratories streamlines sample preparation, analysis, and result validation [10]. In chromatography and spectroscopy, reinforcement learning algorithms optimize instrument parameters, reducing solvent consumption and increasing detection sensitivity [11]. Moreover, AI-driven real-time monitoring systems detect anomalies in analytical workflows, preventing instrument failure and improving long-term reproducibility [12].

GREEN ANALYTICAL CHEMISTRY

Green Analytical Chemistry (GAC) is an emerging field focused on minimizing the environmental impact of analytical methods while maintaining accuracy and efficiency. It integrates sustainable practices, such as reducing hazardous reagents, optimizing energy use, and minimizing waste generation. Additionally, miniaturization and lab-on-a-chip technologies contribute to eco-friendly, cost-effective, and high-throughput analysis [1].

Sustainable Practices (Eco-friendly Reagents, Solvent Reduction, etc.)

Traditional analytical methods often rely on toxic solvents, excessive sample consumption, and high-energy instrumentation, leading to environmental concerns [2]. Green analytical chemistry promotes solvent reduction, replacement of hazardous reagents with eco-friendly alternatives, and energy-efficient processes [3]. For instance, supercritical fluid chromatography (SFC) and micellar liquid chromatography (MLC) use greener solvents to replace toxic organic solvents [4]. Additionally, the adoption of solid-phase microextraction (SPME) and microfluidic sample preparation techniques reduces reagent consumption and waste production [5].

Sustainable practices also extend to energy-efficient analytical instrumentation. For example, low-power spectroscopic techniques such as Fourier-transform infrared (FTIR) and Raman spectroscopy enable rapid, non-destructive analysis with minimal environmental footprint [6]. Furthermore, AI-driven predictive maintenance in analytical instruments improves longevity and reduces unnecessary energy consumption [7].

Miniaturization and Lab-on-a-Chip Technologies

Advancements in microfluidics and lab-on-a-chip (LOC) technology have revolutionized analytical chemistry by enabling rapid, portable, and high-throughput analysis with minimal resource consumption [8]. These technologies integrate multiple analytical steps, such as sample preparation, separation, and detection, onto a single microdevice, significantly reducing reagent and sample volumes [9]. LOC systems are extensively applied in point-of-care diagnostics, environmental monitoring, and pharmaceutical analysis due to their ability to perform real-time, on-site testing with high sensitivity and specificity [10].

Additionally, miniaturized analytical devices contribute to sustainability by reducing plastic and glassware waste, which is a major concern in conventional laboratory settings [11]. For instance, paper-based analytical devices (PADs) provide an inexpensive, biodegradable alternative for chemical sensing applications [12]. Emerging 3D-printed microfluidic devices further enhance the accessibility and customization of green analytical tools [13].

MICROFLUIDICS & LAB-ON-A-CHIP TECHNOLOGIES

Microfluidics and lab-on-a-chip (LOC) technologies have revolutionized analytical chemistry by miniaturizing laboratory functions onto compact, portable devices. These systems enable rapid, cost-effective, and highly sensitive chemical and biological analyses with minimal sample and reagent consumption [1]. The integration of microchannels, sensors, and automated fluid handling in LOC platforms has led to significant advancements in diagnostics, environmental monitoring, and pharmaceutical research [2].

Portable Analytical Devices

Portable analytical devices leverage microfluidic platforms to perform on-site and real-time testing, eliminating the need for centralized laboratories. These devices, often integrated with smartphone-based detection systems, electrochemical sensors, and wireless communication modules, enable point-of-care (POC) diagnostics, food safety monitoring, and forensic investigations [3].

One prominent example is paper-based microfluidic devices (μ PADs), which provide a low-cost, eco-friendly solution for detecting chemical and biological analytes [4]. In medical applications, portable LOC biosensors can detect biomarkers for diseases such as diabetes and cancer with high sensitivity, making personalized healthcare more accessible [5]. Additionally, wearable microfluidic patches allow continuous monitoring of physiological parameters, such as glucose levels and electrolyte balance, without invasive procedures [6].

Real-time and High-throughput Analysis

Microfluidic platforms enable real-time and high-throughput chemical and biological analyses, reducing the time required for testing while enhancing accuracy and reproducibility. By incorporating automated sample processing, parallel assays, and integrated sensors, these systems streamline drug discovery, environmental pollutant detection, and food quality assessments [7].

Advances in droplet-based microfluidics have improved reaction efficiency by allowing controlled mixing of nanoliter-scale liquid droplets, making them ideal for single-cell analysis, enzymatic reactions, and high-throughput screening [8]. Furthermore, lab-on-a-chip mass spectrometry (LOC-MS) enhances molecular identification by integrating microfluidic sample preparation with direct MS analysis, reducing sample loss and contamination [9].

Furthermore, real-time microfluidic sensors in conjunction with Artificial Intelligence (AI) algorithms can process and analyze massive volumes of data, increasing pattern identification and decision-making in clinical diagnostics and environmental monitoring [10]. These technologies are pushing the boundaries of analytical chemistry, allowing faster, more accurate, and field-deployable solutions for a variety of sectors [11].

CHALLENGES & FUTURE TRENDS

Despite rapid advancements, analytical chemistry faces several challenges, including standardization, cost, and sustainability. Standardization and regulatory compliance remain critical as global industries require harmonized protocols to ensure accuracy, reproducibility, and acceptance of analytical methods in pharmaceuticals, environmental safety, and food testing [6]. Cost and instrumentation complexity pose significant barriers, as advanced techniques like NMR, mass spectrometry, and microfluidic LOC systems demand high initial investment and specialized training [7]. Sustainability and accessibility are emerging priorities, with research focusing on green analytical chemistry, eco-friendly reagents, miniaturization, and AI-driven automation to reduce environmental impact while making advanced analytical tools more affordable and globally accessible [8]. Future developments will likely integrate nanotechnology, AI, and decentralized diagnostic platforms to improve efficiency, affordability, and real-time analytical capabilities across diverse applications [9 - 18].

CONCLUSION

Analytical chemistry has undergone remarkable advancements, integrating high performance chromatography, spectroscopy, artificial intelligence, and green chemistry principles to enhance precision, efficiency, and sustainability. High-Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), Mass Spectrometry (MS), and Nuclear Magnetic Resonance (NMR) spectroscopy have transformed chemical analysis in pharmaceuticals, environmental monitoring, food safety, and forensic research. The adoption of AI and machine learning has streamlined data processing, automated complex analyses, and minimized human error, significantly improving reproducibility and

throughput. Additionally, green analytical chemistry and microfluidic lab-on-a-chip technologies are addressing environmental concerns by promoting sustainable, portable, and real-time analytical solutions. Despite these advancements, challenges such as instrumentation complexity, high costs, and standardization issues remain key areas for future research. Moving forward, the integration of nanotechnology, AI-driven automation, and decentralized diagnostic platforms will play a crucial role in shaping the future of analytical chemistry, making it more accessible, efficient, and environmentally responsible.

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