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Review Paper

Recent Advances in Green Analytical Chemistry

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ABSTRACT

Green Analytical Chemistry (GAC) is an emerging scientific discipline that incorporates the principles of green chemistry into analytical practices with the objective of minimizing the environmental burden and potential risks to human health associated with conventional chemical analytical procedures.The 12 principles of green chemistry provide a strategic framework for the integration of Green Analytical Chemistry (GAC) across diverse scientific and industrial applications.Advancements in chromatographic and spectroscopic instrumentation have further contributed to greener analytical practices by enabling rapid analysis, lower energy consumption, and reduced reagent usage. Techniques such as ultra-high-performance liquid chromatography (UHPLC), supercritical fluid chromatography (SFC), and portable spectroscopic systems have improved analytical sensitivity and throughput with minimal ecological impact

INTRODUCTION

Green Analytical Chemistry (GAC) is an emerging scientific discipline that incorporates the principles of green chemistry into analytical practices with the objective of minimizing the environmental burden and potential risks to human health associated with conventional chemical analytical procedures[1].Green chemistry principles are being integrated into research and industry, driving sustainable tech and reducing environmental impact. Safety for humans and ecosystems is being prioritized.Traditional analytical methods can be pretty harsh on the planet . The focus is shifting towards greener alternatives that reduce waste, energy consumption, and environmental impact.A new framework is taking shape, focusing on reducing environmental footprint while keeping performance intact.Toxic reagents are being replaced, waste production is being minimized, and energy efficiency is being improved.Sustainable practices are being prioritized, waste prevention is being emphasized, and environmentally friendly solvents and conditions are being chosen. Energy consumption

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is also being reduced.Green Analytical Chemistry principles are rooted in the wider framework of green chemistry, focusing on the avoidance of harmful substances, reduction of waste formation, and enhancement of energy efficiency throughout analytical procedures [2-4].By minimizing the utilization of hazardous reagents, reducing energy requirements, and mitigating the production of toxic waste, Green Analytical Chemistry (GAC) aims to promote analytical methodologies that are environmentally sustainable and resource-efficient. The conceptual framework of GAC is grounded in the 12 principles of green chemistry, which serve as a systematic guideline for the development and application of eco-friendly, safe, and sustainable analytical procedures[5].Green Analytical Chemistry (GAC) represents a transformative approach to chemical analysis, emphasizing environmental sustainability, resource efficiency, and ecological responsibility in analytical practices. Through the incorporation of the 12 principles of green chemistry, GAC seeks to minimize the environmental and health-related impacts associated with conventional analytical methodologies while fostering innovation in the development of sustainable analytical technologies. As global scientific and regulatory efforts increasingly focus on the monitoring and management of emerging contaminants, GAC has become a critical framework for advancing environmentally benign and efficient analytical strategies[7].The significance of Green Analytical Chemistry (GAC) extends beyond its direct environmental advantages by promoting an integrated and sustainable approach to chemical analysis. Through the emphasis on real-time and in-process monitoring of analytical and chemical reactions, GAC facilitates the early identification and mitigation of process inefficiencies and hazardous by-products, thereby contributing to pollution prevention at the source. Furthermore, the incorporation of chemometric techniques enhances analytical accuracy, precision, and operational efficiency by enabling advanced multivariate data analysis while reducing reagent consumption and resource utilization. This transition from conventional reactive methodologies to proactive and preventive analytical strategies underscores the transformative role of GAC in redefining contemporary practices in analytical chemistry.

History of green analytical chemistry

The roots of green analytical chemistry can be traced to the environmental awareness movements of the 1960s and 1970s, when concerns about pollution, toxic chemicals, and industrial waste began influencing scientific research and regulation.

A major milestone came in 1991 when Paul Anastas introduced the concept of green chemistry at the United States Environmental Protection Agency. In 1998, Paul Anastas and John Warner formally published the **12 Principles of Green Chemistry**, which became the foundation for environmentally safer chemical practices.

Analytical chemistry laboratories were recognized as significant consumers of:

- Hazardous solvents
- Chemical reagents
- Energy
- Disposable materials

This led scientists to adapt green chemistry ideas specifically for analytical procedures.

Development of Green Analytical Chemistry

The term “green analytical chemistry” began gaining attention during the late 1990s and early 2000s. Researchers aimed to redesign analytical methods to:

- Minimize toxic reagent use
- Reduce waste generation
- Lower energy consumption
- Improve operator safety

- Enable sustainable laboratory practices

Key developments included:

- Miniaturization of instruments
- Microscale and nanoscale analysis
- Solvent-free techniques
- Automation and online monitoring
- Use of renewable or biodegradable materials

Important Milestones

1990s: Introduction Phase

Scientists started modifying classical analytical methods to make them less polluting. Attention focused on reducing organic solvent consumption in chromatography and extraction methods.

Early 2000s: Establishment of Principles

Researchers proposed specific principles for green analytical chemistry. These principles emphasized:

- Direct analytical techniques
- Reduced sample size
- In situ measurements
- Safer solvents
- Multi-analyte methods

2010: The 12 Principles of Green Analytical Chemistry

Miguel de la Guardia and Salvador Garrigues helped formalize the field by proposing the **12 Principles of Green Analytical Chemistry**.

These principles encouraged:

1. Minimal sample preparation
2. Minimal reagent consumption
3. Reduction of waste
4. Energy-efficient methods
5. Use of safer chemicals
6. Real-time analysis

Modern Era

Today, green analytical chemistry is widely used in:

- Pharmaceutical analysis
- Environmental monitoring
- Food quality control
- Clinical diagnostics
- Industrial process monitoring

Modern techniques often associated with the field include:

- Supercritical fluid chromatography
- Capillary electrophoresis
- Biosensors
- Lab-on-a-chip systems
- Spectroscopic methods without reagents

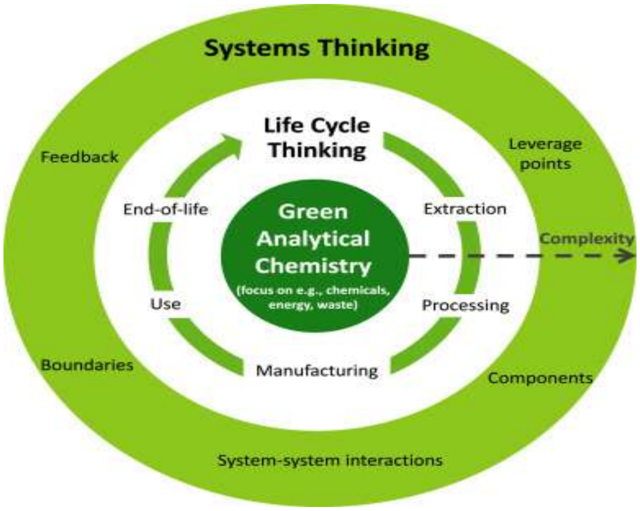
Significance

Green analytical chemistry helps:

- Protect the environment
- Reduce laboratory costs
- Improve laboratory safety
- Support sustainable development goals
- Reduce carbon footprint in scientific research

Principle of green analytical chemistry

The 12 principles of green chemistry provide a strategic framework for the integration of Green Analytical Chemistry (GAC) across diverse scientific and industrial applications. For example, the principle of atom economy emphasizes the design and optimization of chemical reactions to maximize the incorporation of reactant atoms into the desired products, thereby minimizing waste generation. Likewise, the principle advocating the use of safer solvents and auxiliaries has stimulated the development of sustainable extraction and separation methodologies, including solid-phase microextraction (SPME) and supercritical fluid chromatography (SFC), which significantly reduce solvent consumption and environmental impact [9] .



Advancement of greeen analytical chemistry

Recent advances in Green Analytical Chemistry (GAC) have focused on the development of sustainable, energy-efficient, and environmentally benign analytical methodologies that minimize the use of hazardous chemicals and reduce waste generation. Significant progress has been achieved through the adoption of miniaturized and solvent-free sample preparation techniques, such as solid-phase microextraction (SPME), stir-bar sorptive extraction (SBSE), and microextraction by packed sorbent (MEPS). In parallel, the application of green solvents, including ionic liquids, deep eutectic solvents, and supercritical fluids, has enhanced extraction efficiency while reducing environmental toxicity [10].

Advancements in chromatographic and spectroscopic instrumentation have further contributed to greener analytical practices by enabling rapid analysis, lower energy consumption, and reduced reagent usage. Techniques such as ultra-high-performance liquid chromatography (UHPLC), supercritical fluid chromatography (SFC), and portable spectroscopic systems have improved analytical sensitivity and throughput with minimal ecological impact [11]. Additionally, the integration of automation, artificial intelligence, and chemometric tools has optimized analytical workflows, improved resource utilization, and enhanced data reliability.

The emergence of biodegradable materials, renewable sorbents, and nanostructured adsorbents has also expanded the scope of environmentally sustainable analytical procedures. Furthermore, lifecycle assessment (LCA) and greenness assessment metrics, including the Analytical Eco-Scale, AGREE, and GAPI tools, are increasingly employed to evaluate and compare the environmental performance of analytical methods [12]. Collectively, these developments demonstrate the growing emphasis on sustainability and innovation in modern analytical science.

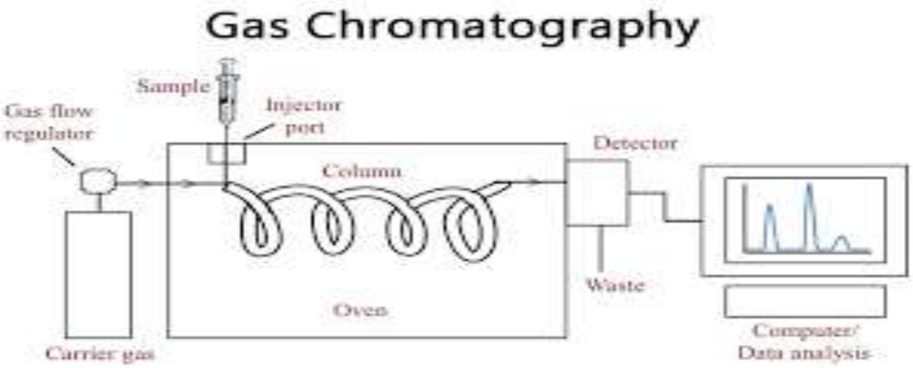
Technological Advancements in Green Analytical Practices

Technological Advancements in Green Analytical Practices refer to the development and implementation of sustainable analytical technologies designed to minimize environmental impact, reduce chemical consumption, and enhance energy efficiency in analytical processes. Recent advancements include the adoption of miniaturized and automated analytical systems, solvent-free or low-solvent extraction techniques, and the use of environmentally benign reagents and materials [13]. Techniques such as ultra-high-performance liquid chromatography (UHPLC), supercritical fluid chromatography (SFC), capillary electrophoresis (CE), and portable spectroscopic devices have significantly improved analytical performance while reducing waste generation and energy requirements. Additionally, the integration of artificial intelligence, chemometrics, and sensor-based technologies has optimized analytical workflows, enhanced precision, and promoted resource-efficient laboratory practices. These innovations collectively support the principles of Green Analytical Chemistry by advancing sustainable, accurate, and cost-effective analytical methodologies[14].

Green Extraction and Purification Methods

Sustainable Gas Chromatography and Liquid Chromatography

Sustainable Gas Chromatography and Liquid Chromatography involve the application of environmentally responsible practices in chromatographic analysis to minimize solvent consumption, energy usage, and hazardous waste generation while maintaining high analytical performance. In gas chromatography (GC), sustainability is achieved through the use of shorter and narrower columns, rapid temperature programming, energy-efficient instrumentation, and reduced carrier gas consumption, including the adoption of hydrogen as an alternative carrier gas [15]. In liquid chromatography (LC), green strategies include the replacement of toxic organic solvents with safer alternatives, solvent recycling, miniaturization of chromatographic systems, and the implementation of ultra-high-performance liquid chromatography (UHPLC) to decrease analysis time and solvent usage . Additional advancements such as supercritical fluid chromatography (SFC), microflow LC systems, and automated sample preparation techniques further contribute to sustainable chromatographic practices. The integration of green solvents, renewable materials, and energy-efficient technologies has significantly enhanced the environmental compatibility of chromatographic methods. These developments align with the principles of Green Analytical Chemistry by promoting safer, cost-effective, and resource-efficient analytical procedures.Modern gas chromatography (GC) systems are equipped with advanced safety mechanisms to minimize operational hazards associated with carrier gases and high-pressure systems. These safety features include integrated leak detection systems, automated shut-off valves, and precise flow-control regulators that ensure safe and stable instrument operation. Furthermore, the implementation of on-demand electrolytic hydrogen generators eliminates the necessity for high-pressure hydrogen gas cylinders, thereby significantly reducing storage-related risks and enhancing overall laboratory safety [16].In the field of liquid chromatography, the transition toward greener analytical methodologies has been driven by efforts to reduce organic solvent consumption and to investigate environmentally safer alternative solvents. Conventional liquid chromatography methods typically require substantial volumes of organic solvents, leading to increased environmental burden, hazardous waste generation, and higher operational costs. Consequently, the development of sustainable chromatographic strategies has become a major focus in modern analytical chemistry[17].



Green Supercritical Chromatographic Technique

It is an environmentally sustainable chromatographic approach that utilizes supercritical fluids, predominantly supercritical carbon dioxide (CO_2), as the primary mobile phase for analytical separations. This technique significantly reduces the consumption of hazardous organic solvents commonly used in conventional liquid chromatography, thereby minimizing toxic waste generation and environmental impact. Owing to the unique physicochemical properties of supercritical fluids, including low viscosity, high diffusivity, and tunable solvating power, green supercritical chromatographic techniques provide rapid, efficient, and high-resolution separations with reduced energy requirements[18]. Additionally, the use of recyclable and non-toxic CO_2 enhances the sustainability, safety, and cost-effectiveness of the analytical process, aligning closely with the principles of Green Analytical Chemistry.Supercritical Fluid Chromatography (SFC) exhibits high analytical versatility and separation efficiency, enabling rapid and high-resolution chromatographic separations as a consequence of the low viscosity and elevated diffusivity of supercritical carbon dioxide (CO_2) employed as the mobile phase. Moreover, the addition of polar organic modifiers, including methanol and ethanol, enhances the polarity and solvating strength of the supercritical fluid, thereby improving the solubility and chromatographic behavior of polar analytes. Consequently, these modifications substantially broaden the analytical applicability of SFC, facilitating the effective separation and characterization of a diverse range of chemical compounds[19-20].The most commonly employed supercritical fluid in Supercritical Fluid Chromatography (SFC) is Carbon Dioxide owing to its relatively low critical temperature (31.1 °C) and critical pressure (73.8 bar). Carbon dioxide is non-toxic, non-flammable, and readily accessible, rendering it an environmentally sustainable alternative to conventional organic solvents. Nevertheless, to enhance the polarity of the mobile phase and improve the solubility of polar analytes, organic modifiers or co-solvents such as Methanol, Ethanol, or Acetonitrile are frequently incorporated into the supercritical fluid system[21.]

future startegy of green analytical chemistry

Future Strategy of Green Analytical Chemistry

The future strategy of green analytical chemistry focuses on making analytical methods more sustainable, energy-efficient, safer, and environmentally friendly while maintaining high analytical performance. Scientists and industries are working toward “zero-waste” and “zero-pollution” analytical systems.

Major Future Strategies

1. Miniaturization of Analytical Systems

Future laboratories will increasingly use:

- Microfluidic devices
- Lab-on-a-chip systems

- Portable analytical instruments

These systems:

- Require very small sample volumes
- Reduce reagent and solvent consumption
- Produce less waste
- Lower energy use

Examples include handheld spectrometers and portable biosensors for field analysis.

2. Development of Solvent-Free and Green Solvent Techniques

Traditional organic solvents are often toxic and hazardous. Future strategies emphasize:

- Water-based analytical systems
- Supercritical fluids
- Ionic liquids
- Deep eutectic solvents
- Solvent-free extraction methods

The goal is to replace harmful chemicals with biodegradable and safer alternatives.

3. Automation and Artificial Intelligence

Integration of:

- Artificial intelligence (AI)
- Machine learning
- Robotics
- Smart sensors

will improve:

- Real-time monitoring
- Automated decision-making
- Error reduction
- Energy optimization

AI-assisted analytical systems can select optimal conditions with minimal chemical use.

4. Real-Time and In Situ Analysis

Future green analytical methods will avoid transporting samples to laboratories by using:

- Remote sensors
- Online monitoring systems
- Wearable analytical devices

This reduces:

- Sample handling
- Storage needs
- Waste generation
- Time and cost

Applications are important in environmental monitoring, healthcare, and industrial quality control.

5. Energy-Efficient Instrumentation

Future instruments will focus on:

- Low-power consumption
- Renewable energy operation
- Energy-saving detector systems

Analytical laboratories are expected to adopt:

- Solar-powered instruments
- Smart energy management systems

6. Waste Reduction and Recycling

Green analytical chemistry aims toward:

- Near-zero waste laboratories
- Recycling of solvents and reagents
- Reusable analytical materials

Future labs may include closed-loop systems where chemicals are continuously purified and reused.

7. Use of Renewable and Biodegradable Materials

Researchers are developing:

- Biopolymer-based sensors
- Natural adsorbents
- Eco-friendly membranes

These materials reduce dependence on petroleum-based laboratory products.

8. Green Nanotechnology

Nanomaterials will be designed with:

- Low toxicity
- Biodegradability
- Environmental safety

Green synthesis methods for nanoparticles will become increasingly important in analytical applications.

9. Digital and Paperless Laboratories

Future strategies include:

- Electronic data management
- Cloud-based analysis
- Virtual laboratories

This reduces paper waste and improves efficiency.

10. Education and International Regulations

Education and international regulations play an important role in promoting sustainable analytical practices across laboratories, industries, and academic institutions worldwide. They help ensure that analytical chemistry develops in an environmentally responsible and safe manner.

1. Education in Green Analytical Chemistry

Importance of Education

Education is essential for:

- Creating environmental awareness among students and researchers
- Training scientists in sustainable laboratory practices
- Reducing hazardous chemical use
- Encouraging innovation in eco-friendly analytical methods

Modern chemistry education increasingly emphasizes sustainability and environmental protection.

Inclusion in Academic Curriculum

Many universities now include topics such as:

- Green chemistry principles
- Green analytical methods
- Waste management
- Sustainable laboratory techniques
- Environmental risk assessment

Courses are introduced in:

- Undergraduate chemistry programs
- Postgraduate analytical chemistry courses
- Pharmaceutical and environmental sciences

Laboratory Training

Students are trained to:

- Use microscale experiments
- Minimize solvent consumption
- Handle chemicals safely
- Reduce laboratory waste
- Use energy-efficient instruments

Green laboratory practices improve both safety and sustainability.

Research and Innovation

Educational institutions encourage research on:

- Green solvents
- Solvent-free analysis
- Portable analytical devices
- Biosensors and nanotechnology
- Waste-free analytical systems

Research funding agencies increasingly support sustainable analytical projects.

Awareness Programs and Workshops

Scientific organizations conduct:

- Workshops
- Seminars
- Training programs
- International conferences

These activities help scientists share new developments in green analytical chemistry.

2. International Regulations in Green Analytical Chemistry

International regulations aim to reduce environmental pollution and ensure safe chemical practices in laboratories and industries.

Role of International Organizations

Several organizations promote green analytical standards, including:

- United Nations Environment Programme
- World Health Organization
- International Organization for Standardization
- United States Environmental Protection Agency
- European Chemicals Agency

These organizations encourage environmentally safe analytical methods and chemical management.

Important International Regulations and Policies

REACH Regulation

European Chemicals Agency introduced the REACH regulation:

- Registration
- Evaluation
- Authorization
- Restriction of Chemicals

Its goals are:

- Safe use of chemicals
- Reduction of hazardous substances
- Protection of human health and the environment

ISO Standards

International Organization for Standardization develops standards related to:

- Laboratory quality management
- Environmental management
- Chemical safety

Important standards include:

- ISO 14001 (Environmental Management Systems)
- ISO/IEC 17025 (Testing and Calibration Laboratories)

Green Laboratory Certification

Many institutions now adopt:

- Sustainable laboratory certification systems
- Energy-saving guidelines
- Waste reduction protocols

Examples include green laboratory initiatives in universities and pharmaceutical industries.

Regulations on Hazardous Chemicals

Countries worldwide regulate:

- Toxic solvents
- Hazardous reagents
- Chemical disposal
- Air and water pollution from laboratories

These regulations encourage the use of:

- Safer solvents
- Low-toxicity reagents
- Waste recycling systems

Global Sustainability Goals

Green analytical chemistry supports the:

- United Nations Sustainable Development Goals (SDGs)

Especially:

- Good Health and Well-being
- Clean Water and Sanitation
- Responsible Consumption and Production
- Climate Action

Universities and industries are expected to:

- Include green analytical chemistry in curricula
- Train scientists in sustainable practices
- Develop international green laboratory standards

Global organizations may introduce sustainability certification systems for analytical laboratories.

Emerging Technologies in Future Green Analytical Chemistry

Some promising technologies include:

- Biosensors
- Nanobiosensors
- Lab-on-a-chip devices
- 3D-printed analytical systems
- Smartphone-based analytical tools
- Portable spectroscopy
- Internet of Things (IoT)-connected instruments

Challenges for the Future

Despite progress, some challenges remain:

- High cost of advanced instruments
- Limited availability of green solvents
- Need for method standardization

- Balancing sensitivity with sustainability
- Training skilled personnel

CONCLUSION

Green analytical chemistry represents an important advancement in modern analytical science by combining accurate chemical analysis with environmental sustainability. It focuses on reducing the use of hazardous chemicals, minimizing waste generation, lowering energy consumption, and improving laboratory safety while maintaining reliable analytical performance. The development of green analytical chemistry has encouraged the adoption of eco-friendly techniques such as miniaturized instruments, solvent-free methods, real-time analysis, biosensors, and automated systems. These innovations help protect human health and the environment while also reducing operational costs in laboratories and industries.

Green analytical chemistry plays a vital role in many fields, including environmental monitoring, pharmaceutical analysis, food safety, clinical diagnostics, and industrial quality control. International regulations, educational programs, and sustainable laboratory practices continue to support its global growth and implementation.

In the future, advances in artificial intelligence, nanotechnology, portable devices, and renewable materials are expected to make analytical methods even more sustainable and efficient. Thus, green analytical chemistry is not only a scientific approach but also an essential step toward achieving sustainable development and a cleaner, safer future for society and the environment.

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