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Review Article

GREEN ANALYTICAL CHEMISTRY : A REVIEW OF ECO-FRIENDLY TECHNIQUES

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Green analytical chemistry (GAC) is developing quickly at the moment, necessitating the establishment of clear, succinct guidance in the form of GAC principles that will aid in greening laboratory operations. Because they fall short of analytical chemistry's requirements, the current green chemistry and green engineering principles need to be revised for application in GAC. This article presents a collection of principles that will be crucial for GAC's future. These principles include some innovative ideas (like using natural reagents) as well as well-known ones (like reducing the use of energy and reagents and eliminating waste, risk, and hazard). The goal of green analytical chemistry is to make analytical processes safer for people and the environment. When evaluating the greenness of an analytical approach, a wide range of factors are taken into account, including the quantity and toxicity of reagents, waste generated, energy consumption, the number of procedural steps, miniaturization, and automation. The eco-scale assessment (ESA), the green analytical procedure index (GAPI), and the national environmental methods index (NEMI) are the three evaluation techniques. Generally, GAC serves as a catalyst for advancing analytical chemistry. The primary challenge of GAC is to balance the reduction of the adverse effects of analytical procedures on the environment with the improvement of the quality of analysis results. Analytical laboratories generate substantial amounts of chemical waste due to extensive solvent use, sample preparation procedures, and energy-intensive instrumentation. Techniques such as chromatography and spectrometry often rely on toxic organic solvents and produce hazardous residues. With increasing global awareness of environmental sustainability and stricter regulatory policies, the need for greener analytical alternatives has become essential.

Key words: Green Chemistry, Eco scale assessment, Energy efficiency, Hazard reduction, NEMI

INTRODUCTION

Green Analytical Chemistry (GAC) emerged as a response to the environmental and health concerns associated with conventional analytical laboratory practices. Traditional analytical methods often require large volumes of hazardous solvents, toxic reagents, and energy-intensive instruments, resulting in significant chemical waste and potential risks to both laboratory personnel and the environment.

The concept of GAC evolved from the broader framework of Green Chemistry, which was formally introduced in the 1990s to promote environmentally friendly chemical processes.[1,2] However, while green chemistry focuses mainly on chemical synthesis and industrial production, analytical chemistry has its own specific challenges—such as sample preparation, solvent use, waste generation at small scales, and high-frequency routine analyses. These differences created the need

for a specialized approach tailored specifically to analytical laboratories.

Green Analytical Chemistry aims to design analytical methods that reduce or eliminate hazardous substances, minimize energy consumption, and decrease waste generation without compromising accuracy, precision, and reliability. It promotes strategies such as[2,3]

- Reducing the quantity and toxicity of reagents and solvents
- Replacing hazardous chemicals with safer or natural alternatives
- Miniaturizing analytical procedures (e.g. microscale techniques)
- Automating processes to reduce errors and exposure
- Improving energy efficiency of instruments
- Implementing proper waste management practices[4]

Benefits Of Green Analytical Chemistry:

1. Human Health : Cleaner air and water reduce lung injuries and health risks from toxic waste. Fewer harmful chemicals improve worker safety and lower risks of fires and explosions. Safer, short-lived pesticides and removal of persistent toxins make food safer. Overall, green practices minimize exposure to harmful substances like hormone disruptors.[4,5]

2. Economy and Business: Higher-yield processes produce more output using less raw material fewer synthesis steps increase production capacity and reduce energy and water use. Reusing waste as feedstock lowers cost and improves efficiency. Better performance means smaller product amounts are needed, boosting competition in the chemical market.[5]

PRINCIPAL OF GREEN ANALYTICAL CHEMISTRY-

1. Direct analytical techniques should be applied to avoid Sample treatment.

Perform measurements directly whenever possible to avoid sample preparation steps that consume reagents and generate waste.

2. Minimal sample size and minimal number of samples are Goals.

Reduce the amount and number of samples analyzed to decrease chemical consumption and waste production.[6]

3. InSitu measurements should be performed.

Carry out analyses at the site of sampling to minimize transportation & preservation.

4. Integration of analytical processes and operations saves energy and reduces the use reagents.

Integrate and combine analytical steps to reduce procedural complexity, time, and resource use.

5. Automation and Miniaturization methods should be selected.

Use automated and miniaturized systems to improve precision while lowering reagent use,

waste generation, and energy consumption[7,8]

6. Avoid derivatization.

Eliminate unnecessary chemical modification steps that require additional reagents and produce extra waste.

7. Generation of a large volume of analytical waste.

Should be avoided and proper management of analytical waste should be provided.

8. Energy efficiency.

Reduce energy consumption by using energy-efficient instruments and conducting analyses at ambient temperature and pressure whenever possible.[8,9,10]

9. Use of safer reagents.

Replace toxic and hazardous chemicals with safer, environmentally friendly alternatives.

10.Use of Renewable (natural) reagents.

Prefer reagents derived from renewable resources or natural sources whenever feasible.[9,10]

Sample Preparation Technique

1. Solid Phase Extraction (SPE)

SPE traps analytes on a solid sorbent. Uses very little solvent and creates less waste. Easy to automate and gives accurate results. Uneven packing can reduce efficiency. Polar compounds may not retain well. Matrix interference can lower recovery. Needs proper optimization for good extraction[10]

2. Quenchers Extraction Methodology

Quenchers are a fast and simple green extraction method. Uses very little organic solvent. Sample is shaken with buffer, $MgSO_4$, and NaCl for extraction. Cleanup uses $MgSO_4$ and PSA to remove impurities. Removes fats,

Table 1: Difference between Analytical Chemistry & Green Analytical Chemistry

Title	Analytical Chemistry	Green Analytical Chemistry
Definition	It is branch of chemistry deal with the separate on, identification and qualification of chemical substance.	The design of chemical product and process that more environmentally benign.
Main focus	Accuracy and precision.	Accuracy reduced hazardous and waste.
Solvent reagent use	Harmful solvent and reagent.	Safer, eco-friendly solvents.
Waste generation	Generate more chemical waste.	Minimize or eliminates waste.
Instrumental methods	High energy requires.	Minimized energy requires
Safety concerns	Higher Exposure risk.	Safer for analysts and environment.
Cost	High cost	Cheaper cost

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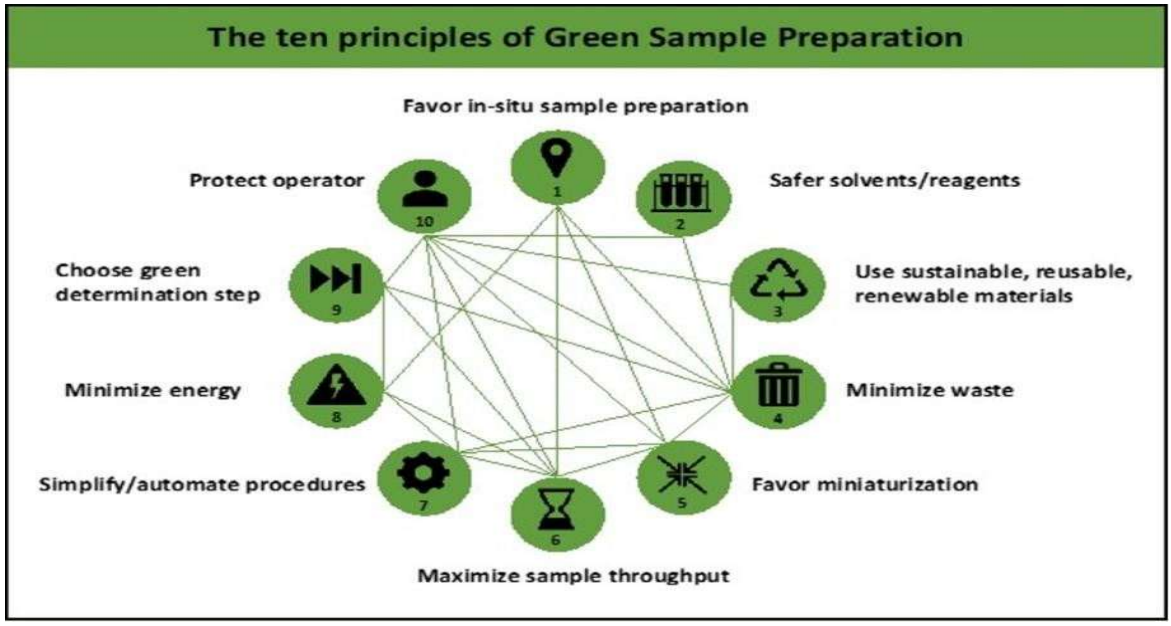


Fig.1: Green Sample Preparation

sugars, and other matrix interferences. Used to extract drugs like amphetamines, opiates, cocaine, and THC from blood.

3. Stir-Bar Sorptive Extraction(SBSE)

SBSEisa green, solvent-free extraction method. Uses a PDMS-coated magnetic stir bar instead of a fiber. Works for volatile and non-volatile analytes. Larger coating gives higher sensitivity than $MgSO_4$ removes leftover water. PSA sorbent removes matrix impurities. Improves extract quality in dispersive SPE. Quenchers extract drugs (amphetamine, opiates, cocaine, THC) from blood. SPME isolates food sample compounds with GC–MS, LC–MS, HPLC, or GC.SPME is cheap, simple [11,12]

4. Pressurized fluid extraction (PFE)

ASE uses high temperature and pressure to speed up extraction. High temperature lowers solvent viscosity and increases analyze solubility. High pressure helps solvent enter matrix pores effectively. Uses less solvent than conventional methods. Allows green solvents like ethanol/methanol. Fast, efficient, and energy saving extraction method.[13]

5. Supercritical Fluid Extraction (SFE)

SFE is an easy, automatic, and eco-friendly extraction method. Uses safe solvents like supercritical CO_2. Works fast with low temperature, protecting sensitive compounds. Gives clean extracts with little or no extra cleanup. Uses very little solvent, making it greener.CO_2 is the most common fluid because it is safe and nontoxic. SFE is quick, selective, and environmentally friendly.

6. Microwave-Assisted Extraction(MAE)

Microwave radiation heats polar molecules to speed up extraction. Heat transfers to solvent, improving analytes release. Microwave range: 300 MHz–100 GHz, ovens use 2.45 GHz. Fast heating and high temperature are major advantages. Simple and efficient operation. Limited solvent heating due to dielectric properties is a drawback.[14,15]

7. Ultrasound-Assisted Extraction(UAE)

MAE uses microwave radiation to speedup extraction. Polar molecules absorb microwaves, causing rapid heating. Solvent heats quickly when in contact with the sample. Microwaves operate from 300 MHz–100 GHz, unlike fixed-frequency ovens. Benefits: fast heating, high temperature, easy operation. Limitation: solvent heating depends on its dielectric constant.[15]

8. Dispersive Liquid–Liquid Microextraction (DLLME)

Uses three phases: aqueous sample, extraction solvent, disperser solvent. Rapid mixing forms fine emulsion for quick analyses transfer. Centrifugation separates phases after extraction. Dense extractant phase collected using a microsyringe. Uses very small solvent/sample volume. Gives high enrichment and recovery. Fast equilibration due to large contact surface.[15,16]

Advantages Of Green Analytical Chemistry

1. Environmental Protection

- Reduces hazardous chemical use
- Minimizes toxic waste generation
- Decreases air, water,and soil pollution

2. Improved Laboratory Safety

- Uses safer solvents (e.g.,water,ethanol instead of toxic organic solvents)
- Reduces exposure to harmful chemicals
- Lowers risk of accidents and health hazards.[16]

3. Cost Reduction

- Less consumption of reagents and solvents
- Reduced waste treatment and disposal costs
- Lower energy consumption.[17]

4.Faster Analysis

- Direct analytical techniques reduces ample preparation steps
- On-site and in-line monitoring save time.[18,19]

5. Compliance with Regulations

- Meets environmental and safety regulations

Limitations of Green Analytical Chemistry

1. Analytical Sensitivity and Accuracy

- Some green solvents or reagents may have lower solubility or reactivity, which can reduce the sensitivity or precision of certain analyses.

- Balancing "green" approaches with analytical performance can be challenging.

2. Limited Scope of Application

- Not all analytical techniques can be easily adapted to green methods.
- Complex matrices (like environmental or biological samples) sometimes require traditional solvents or reagents for effective extraction and detection.

3. Method Development Time

- Developing a green analytical method can be more time-consuming, as it often involves optimizing alternative solvents, reducing waste, and validating performance.[19,20,21]

Recent Advancement in Green Analytical Chemistry

(a) Advanced Green Sample Preparation Method

Modern research is strongly focusing on greener sample prep techniques that drastically reduce or eliminate harmful solvents.

- Techniques using deep eutectic solvents (DES), ionic liquids (ILs), supramolecular or switchable solvents that are less toxic and more biodegradable. These help extract analytes without large volumes of organic solvents.[22]
- Development of microextraction and nano-enabled sorbent materials (e.g., metal-organic frameworks or MOFs) for efficient separation and preconcentration with minimal waste.[22,23]

(b) Greener Chromatographic & Separation Method

Traditional High-Performance Liquid Chromatography (HPLC) and Gas Chromatography (GC) consume large volumes of solvents:

- New approaches optimize chromatographic method design using green metrics and solvent-minimizing strategies, cutting down hazardous mobile phases.
- Efforts include solvent-free techniques and use of supercritical fluids as sustainable extractants that replace conventional organics.[24,25]

(c) Miniturization and effective method

There's a significant shift toward microfluidic devices, miniaturized systems, and automated analytical platforms that use fewer reagents and samples while increasing throughput and precision:

- Micro-and nano-scale analytical systems reduce waste and energy usage.
- Automated workflows also improve efficiency and lower the number of repetitive steps (reducing exposure and hazardous byproducts).[26]

(d) Green Solvent and Sustainable Media

Alternatives to harmful organic solvents are becoming main stream:

- Research increasingly uses water, bio-

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based solvents, and other less toxic media for extraction and separation.[27]

Critical Analysis and Parameter of Green Analtical Chemistry

(a) Health and Safety Benefits

- Less exposure to hazardous reagents for laboratory personnel.
- Reduces toxic by-products that can affect ecosystems.

(b) Technological Innovations

- Development of solvent-free, portable, or real-time sensors.
- Integration with automation and AI for easy workflows.[27,28]

(c) Environmental Sustainability

- Significantly reduces chemical waste, solvent usage, and energy consumption.
- Supports global goals for environmental protection and sustainable development.(28)

Research Gaps in Green Analytical Chemistry.

1. Limited Scope of Green Methods for Complex Samples

- Many green techniques work well for simple matrices (e.g.,water, pharmaceuticals), but struggle with complex matrices like soil, food, or biological fluids.
- **Gap:** Development of universal green methods that retain high selectivity and sensitivity for complex samples.

2. Trade-Off between Greenness and Analytical Performance

- Reducing solvents, reagents, and energy sometimes lowers method sensitivity or precision.
- **Gap:** Designing methods that maintain analytical rigor while being eco-friendly, especially for trace-level detection.[28]

3. Standardization and Metrics

- There is no universally accepted metric to quantify “greenness” of analytical methods.
- Existing tools (e.g., Analytical Eco-Scale, Green Analytical Procedure Index) are useful but inconsistent.
- **Gap:** Standardize devaluation protocols to compare greenness across labs and industries.

4. Limited Development of Green Reagents

- Most green methods still rely on existing solvents or reagents, sometimes substituting only partially.
- **Gap:** Need for novel, biodegradable, or non-toxic reagents for extraction, separation, and detection processes.[29]

5. Energy Efficiency and Automation

- Techniques like microwave-assisted extraction or miniaturized sensors are emerging but not widely adopted.
- **Gap:** Integration of automation, real-time monitoring, and AI-driven methods to minimize energy and resource use.

6. Life-Cycle Assessment (LCA)

- Few studies consider the full environmental footprint of analytical methods—from raw materials to disposal.
- **Gap:** Research on LCA for green analytical procedures to evaluate true environmental impact**.**

7. Scalability and Industrial Adoption

- Green methods are often demonstrated at the laboratory scale, but scaling up to industrial applications is challenging.[29,30]
- **Gap:** Studies on process optimization, cost-benefit analysis,and industrial feasibility for large-scale adoption.

CHALLENGES

1. High costs of green materials and equipment
2. Limited availability and lack of standardized methods
3. Technical limitations insensitivity and selectivity
4. Trade-off between environmental impact and analytical performance
5. Lack of awareness and training
6. Waste management and proper disposal of even green reagent. [30,31]

CONCLUSION

GAC is providing the way for a more sustainable future in science. Green chemistry's tenets include cutting waste, utilizing safer chemicals, and increasing energy efficiency. Green solvents like water and bio-based substitutes, as well as energy-saving approaches like microwave and ultrasound-assisted procedures, demonstrate that analytical chemistry may be both efficient and environmentally friendly. GAC is revolutionizing the way we approach analytical techniques. GAC measures that make it possible to compare various analytical method parameters and procedures in order to identify the less environmentally friendly parts. An great semi-quantitative instrument for lab practice and teaching is the Analytical Eco-scale. In the field of analytical chemistry, a significant application of greenness evaluation methodology has taken place, monitoring the growth of the idea of green chemistry when selecting a solvent or reagent for optimal operation. green analytical chemistry standards. For laboratory practice and teaching, Analytical Eco-Scale can be a great semi-quantitative instrument. It may be applied to any established or novel process, is simple and quick to use, and has clear evaluation criteria. Concerns over the environmental effects of chemical and analytical research procedures, notably the use of hazardous solvents and reagents, have become urgent. Following the development of the idea of "green chemistry" in recent decades, the analytical chemistry field has seen a significant use of greenness evaluation approaches. This

study does not involve experiments on animals or human subjects.

FUTURE PERSPECTIVES

GAC has the potential to revolutionize the pharmaceutical sector by improving the efficiency, affordability, and environmental sustainability of analytical procedures. Using GAC in pharmaceutical analysis has several advantages, including decreased waste, lower solvent use, energy savings, and improved safety, all of which greatly support the sector's sustainability objectives. Advances in analytical technologies will have a big impact on GAC's future in the pharmaceutical industry. More encouraging laws will probably be created to promote the use of green analytical methods as government and regulatory bodies come to understand the significance of sustainability. Regulatory agencies like the FDA and EMA might update their policies to specifically incorporate green chemistry.

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Conflict of Interest

The authors declare that they have no conflict of interest