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A Review on Green Analytical Chemistry

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ABSTRACT:

The field of analytical chemistry is undergoing a transformation toward sustainability by minimizing hazardous reagents, reducing waste, and optimizing energy consumption. This review examines strategies for eco-friendly analysis—from sample preparation through detection—emphasizing automation, miniaturization, and process intensification. A greener workflow not only curbs toxic by-products but also supports safer laboratory practices and aligns with broader environmental goals. Critical evaluation of solvent selection, instrument design, and procedural modifications highlights pathways to implement benign methodologies without compromising analytical performance. This synthesis outlines current advances, practical guidelines, and future directions for embedding green principles throughout the analytical lifecycle.

KEYWORDS: - Green analytical chemistry; Sustainable analysis; Waste minimization; Eco-friendly solvents; Process intensification; Miniaturization; Automation; Benign methodologies; Environmental assessment tools; Green principles

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INTRODUCTION:

Green chemistry emerged to revolutionize chemical research by embedding environmental stewardship into every phase of chemical production and analysis. Traditional analytical methods often rely on toxic reagents, generate substantial waste, and consume high energy. In contrast, green analytical chemistry seeks to redesign workflows—emphasizing waste prevention, the use of nonhazardous materials, and energy-efficient procedures—while maintaining rigorous analytical performance. This paradigm shift not only reduces ecological and health risks but also fosters innovation in instrument design, automation, and miniaturization, ultimately advancing both sustainability and safety in laboratories worldwide.

DEFINITION:

The aim of sustainable chemical testing is tried to employ testing techniques that produce minimal dangerous byproducts, prioritizing user safety and environmental protection.

Developing new analytical methodologies

Changing an established chemical method to incorporate practices that either rely on less dangerous substances or limit the quantity of hazardous chemicals used is described as "adapting existing procedures to enhance safety and decrease harm by substituting or minimizing hazardous compounds wherever possible"

HISTORY:

Along with papers from the royal society of chemistry, chemical interactions released the first book on green analytical chemistry in 1990. A cutting edge approach to using creating and processing chemicals that reduces risks to environment and public health like pure chemistry the economics of environmentally friendly atoms and molecules Poul Anastas developed the twelve principles of green chemistry which deal with eliminating potentially dangerous or damaging substances from the synthesis production and usage of chemical based goods although the goal of a green chemistry strategy is to incorporate as a many of the principles as possible into specific synthesis phases it is not feasible to concurrently meet the requirements of all twelve criteria throughout the procedures.

PRINCIPLE:

i. **Prevention**
Design analytical methods that avoid waste generation rather than treating waste after it is created.

ii. **Atom Economy**
Maximize the use of all reagents; minimize by-product formation in sample preparation and derivatization.

iii. **Less Hazardous Chemical Syntheses**
Replace or reduce toxic reagents and solvents in analytical protocols.

iv. **Designing Safer Chemicals**
Favor reagents and derivatizing agents that pose minimal health and environmental risks.

v. **Safer Solvents and Auxiliaries**
Use benign solvents (e.g., water, ethanol, ionic liquids) or eliminate solvents via solvent-free techniques.

vi. **Design for Energy Efficiency**
Implement ambient-temperature or microwave-assisted sample preparation to reduce energy consumption.

vii. **Use of Renewable Feedstocks**
Employ naturally derived reagents or biopolymers for sample treatment and extraction.

viii. **Reduce Derivatives**
Minimize derivatization steps by using direct analysis techniques like ambient-ionization mass spectrometry.

ix. **Catalysis**
Introduce catalytic systems to speed reactions and reduce reagent quantities in preparative protocols.

x. **Design for Degradation**
Select reagents and sorbents that degrade to innocuous products at end of life.

xi. **Real-Time Analysis for Pollution Prevention**
Integrate in-line or at-site monitoring tools to detect analytes without generating hazardous sampling waste.

xii. **Inherently Safer Chemistry for Accident Prevention**
Simplify procedures and remove high-pressure or high-temperature steps to lower the chance of spills, leaks, or explosions.

Fig: 1 Green analytical chemistry principles

TYPES OF GREEN ANALYTICAL CHEMISTRY:

- Solvent free techniques: -
  - Avoid the use of organic solvents, which are often toxic and non-renewable.
  - Ex: - solid phase microextraction (SPME)
- Miniaturized analytical techniques: -
  - Use very sample and reagent volumes, reducing waste.
  - Ex: - microfluidic system, microextraction by packed sorbents
- InSite and On-site analysis: -
  - Analyse samples at point of origin to avoid transport and degradation.
  - Ex: - Biosensors, FTIR Spectrometer
- Use of Green Solvents: -
  - Replace toxic solvents with environmentally benign alternatives.
  - Ex: - Water, ethanol, supercritical Co2
- Energy-Efficient Techniques: -
  - Reduce energy consumption during analysis.

- Ex: - Microwave- assisted Extraction, LED based detectors

- Water Minimization Methods: -
  - Reduce or recycle waste generated during analysis.
  - Ex: - Solid -phase extraction (SPE), Reagent recycling systems.
- Automation and Integration: -
  - Automate processes to improve efficiency and reduce human error.
  - Ex: - Flow injection analysis (FIA), Sequential injection analysis (SIA).
- Non – Destructive Testing Methods: -
  - Preserve the sample and reduce the need for additional chemicals.
  - Ex: - NIR (Near – Infrared Spectroscopy), x-ray techniques.

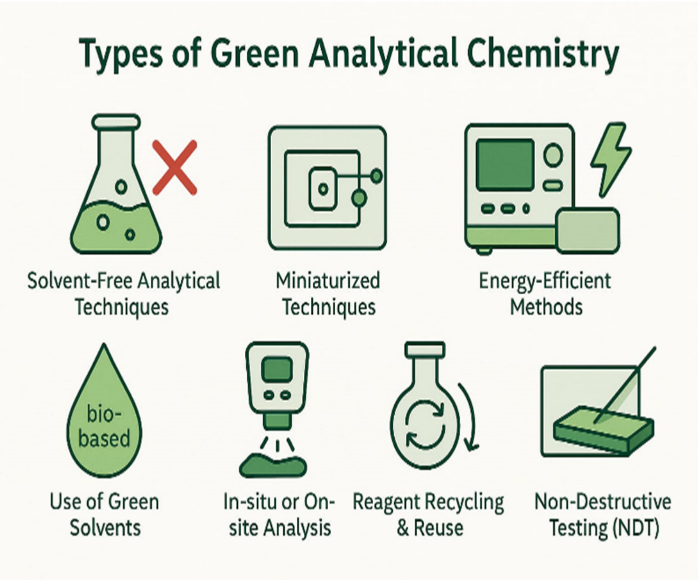

Fig: 2 Types of Green Analytical Chemistry

Types of Green Analytical Solvents:

Water:
As a naturally abundant and non-toxic solvent, water plays a vital role in numerous industrial operations, from chemical extractions to reaction media. Its effectiveness is further improved through techniques like aqueous biphasic systems, which expand its application in green chemistry.

Supercritical Fluids:

Supercritical carbon dioxide ($scCO_2$) is one of the most commonly applied eco-friendly solvents. Owing to its non-toxic nature, recyclability, and relatively mild operating requirements, it is extensively used in processes such as decaffeination, material extraction, and industrial cleaning.

Ionic Liquids:

These liquids consist of organic cations combined with inorganic anions. They are characterized by negligible vapor pressure, customizable physical and chemical properties, and are widely utilized in separation technologies, catalytic reactions, and electrochemical applications.

Deep Eutectic Solvents (DESs):

Prepared by blending two or more substances that interact to significantly reduce the melting point, DESs are inexpensive, biodegradable, and environmentally benign. They find practical uses in biomass conversion, metal recovery, organic synthesis, and bio-refinery processes.

Ethyl Lactate:

Produced from lactic acid, ethyl lactate is commonly employed in surface cleaning formulations and coating applications.

d-Limonene:
Naturally obtained from citrus peels, d-limonene functions as an efficient cleaner and degreasing agent.

Alcohols and Glycerol:

Renewable alcohols, such as ethanol, along with glycerol (a co-product of biodiesel manufacture), represent sustainable, bio-based options for use in chemical reactions and product formulations.

Organic Carbonates:

Compounds like dimethyl carbonate (DMC) are recognized for being biodegradable and non-toxic. They serve in the synthesis of polycarbonate plastics and also act as valuable solvents in organic transformations.

Fluorous solvents:

These specialized solvents are known for their high selectivity and minimal ecological impact, making them useful in organic synthesis and separation processes.

Benefits of Green Solvents:

- Lower Toxicity: Designed with safety in mind, green solvents present reduced health risks and decrease harmful emissions and chemical waste.
- Biodegradability: Many of these solvents naturally decompose, preventing long-term accumulation in ecosystems.
- Low Volatility: With limited emission of volatile organic compounds (VOCs), they help curb air pollution and smog formation.

TOOLS OF GREEN ANALYTICAL CHEMISTRY

1.) National Environmental Method Index (NEMI): -

The National Environmental Methods Index (NEMI), established by the Methods and Data Comparability Board, is the most extensive repository of eco-aware analytical procedures. First detailed by Keith and colleagues in 2007, NEMI presents a four-quadrant circular diagram: one quadrant represents persistence, bioaccumulation, and toxicity (PBT); the second denotes hazardous characteristics; the third covers corrosiveness; and the fourth indicates waste output. Quadrants shaded green signify compliance with environmentally preferred criteria, whereas unshaded portions indicate shortcomings. This visualization incorporates parameters such as chemical class, acidity or alkalinity, and disposal volume, allowing straightforward side-by-side assessment of method sustainability.

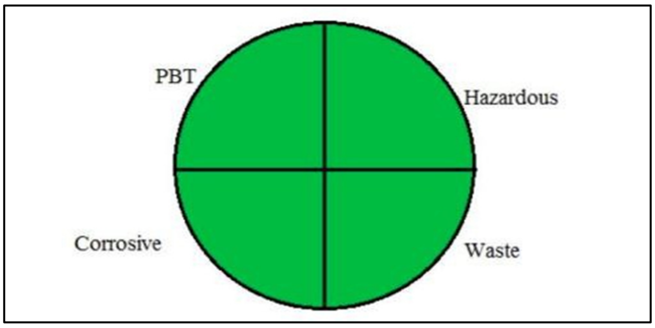

Fig: 3 National Environmental Method Index (NEMI)

2.) Analytical eco-scale/eco-scale assessment (AES/ESA):

The Analytical Eco-Scale, launched in 2012, provides a hybrid qualitative–quantitative framework for gauging the environmental footprint of laboratory protocols. Starting from an ideal value of 100, it subtracts penalty points assigned for reagent and solvent volumes, energy consumption, and waste output. Scores exceeding 75 signify exemplary green performance; values between 50 and 75 denote acceptable practice; and those under 50 reveal significant ecological shortcomings. This tool's strengths include ease of calculation, provision of a clear numerical indicator, and evaluation across diverse sustainability criteria. However, it may overlook nuanced procedural aspects, and its aggregate score lacks granularity regarding specific ecological burdens, which can hinder targeted remediation. Despite these limitations, the Eco-Scale marks a notable improvement over older assessments and remains widely used alongside GAPI and AGREE.

3.) Green analytical Procedure Index (GAPI): -

GAPI is a comprehensive tool designed to evaluate the environmental sustainability of analytical methods, covering every stage from sample collection to final detection. Launched in 2018, its results are displayed as a visual symbol featuring a central pentagon surrounded by four additional pentagons, each representing one of five categories: technique type, sample handling, sample preparation, chemicals and reagents, and instrumentation. The assessment utilizes a traffic light color system—red, yellow, and green—to rate fifteen individual criteria. Its main advantage lies in its straightforward approach, addressing various elements of an analytical procedure. While GAPI overcomes significant limitations found in the NEMI tool, it is limited by its qualitative nature and the complexity of its graphical output.

Key Benefits of the AGREE Tool:

- The tool offers a thorough assessment by incorporating all twelve green analytical chemistry principles.
- Users can customize certain parameters, making the tool adaptable to various analytical methods.
- The pictogram provides a clear visual summary, highlighting both strengths and weaknesses of the evaluated method.
- It delivers both qualitative insights and quantitative scores for comprehensive evaluation.
- The software is user-friendly and provides rapid feedback.

Evolution of Green Analytical Chemistry: -

The progression of green analytical chemistry reflects continual refinement of techniques and assessment strategies. Early efforts emphasized simple solvent swaps and microscale extractions. Later, comprehensive greenness metrics (e.g., AGREE) enabled holistic method optimization.

Case Study: Greening HPLC Analysis
A conventional reverse-phase HPLC assay for pharmaceutical impurities
was reengineered by:

- Replacing acetonitrile with ethanol–water mobile phases
- Reducing flow rate via core–shell columns to cut solvent use by 60%
- Implementing on-line solid-phase extraction to eliminate off-line sample cleanup
- Applying AGREE scoring to achieve a 25% greenness improvement

This example illustrates how systematic method redesign, guided by quantitative metrics, yields significant environmental and cost benefits without compromising resolution or sensitivity.

Greenness assessment of the system: -

In this publication, the existing system was evaluated in relation to the target field demonstrator. Wojnowski has provided open-source software on his website, which is accessible at no cost. The outcomes of the case studies using the AGREE tool, along with the specific data used to generate the pictogram, are presented. Each of the twelve green analytical chemistry principles was assigned equal importance in the assessment. The system's design relies on direct enrichment of surface water samples using a separation cartridge.

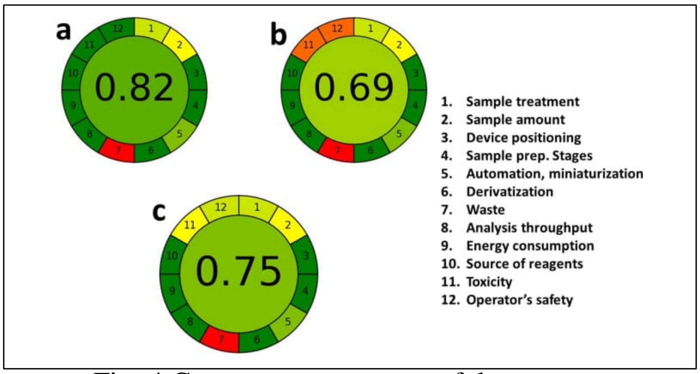

Fig: 4 Greenness assessment of the system

A two-step separation technique incorporates both chromatographic and ion mobility methods. Presently, this arrangement exists as a laboratory prototype with sample processing performed separately from the detection phase. Up to 100 microliters of surface water can be concentrated on a trapping device. The examination is currently conducted outside the direct instrument workflow. Simple removal of particulate matter from the sample is required. The full apparatus is reduced in size; however, the components lack integrated software control, resulting in partial automation only. Chemical modification of target compounds is unnecessary. Waste generation includes only the volume of the enriched specimen and the combined amount of water and ethanol utilized during analysis, totalling 112 microliters per test.

Six analytes were successfully resolved within a 400-second timeframe. Individual energy usage of components was assessed, with a cumulative consumption of 0.04 kilowatt-hours per sample. All liquids utilized were sourced conventionally. The presence of ethanol ensures the mobile phase is free from harmful solvents, although ethanol itself is highly combustible. This method achieved an eco-efficiency score of 0.73, with 1.00 indicating the highest level of sustainability. Evaluating the system during its development helps pinpoint areas for improvement within the green chemistry framework. Key aspects such as sample processing, equipment placement, and reagent sourcing offer opportunities for further enhancement. Full automation is possible by integrating the nano-UHPLC, loading pump, cartridge changer, and ESI-IMS into a single software platform. Housing all components together and powering the system with rechargeable batteries increases mobility, allowing for on-site sample processing and device setup. Ethanol sourced from renewable materials can be used, although current bioethanol production does not yet meet the purity required for HPLC applications. With these upgrades, the eco-efficiency score could rise to 0.92.

To provide a clearer perspective, this approach was compared to a conventional laboratory protocol for analyzing 17 substances in surface water. The benefits of miniaturization are evident, as the traditional method generates much more waste (by a factor of 76), relies on hazardous acetonitrile, and consumes significantly more energy due to the laboratory-scale LC-MS system. As a result, the conventional protocol achieves a lower score of 0.47.

APPLICATIONS:

1. Applications of Green Analytical Techniques
   - Pharmaceutical Industry
   - Rapid analysis of drugs with minimal solvents.
   - Green sample preparation methods (e.g., solid-phase microextraction, microwave-assisted extraction).
   - Reduces toxic solvent waste in quality control labs.
2. Environmental Monitoring
   - Detection of pollutants, pesticides, heavy metals, and pharmaceuticals in water, soil, and air.
   - Portable green devices (biosensors, microfluidic chips) for field analysis.
   - Eco-friendly monitoring of greenhouse gases and contaminants.
3. Food and Agriculture
   - Analysis of food additives, contaminants, and nutritional components using solvent-free or low-solvent methods.
   - Green chromatography for pesticide residue detection.
   - Non-destructive techniques like ne ar-infrared (NIR) and Raman spectroscopy for quality testing.
4. Clinical and Biomedical Applications
   - Safer analytical procedures for biological fluids (blood, urine, serum).
   - Green electrochemical sensors for disease biomarkers.
   - Minimizes use of hazardous reagents in diagnostic labs.
5. Forensic Science
   - Eco-friendly detection of drugs of abuse, explosives, and toxins.
   - Miniaturized analytical systems for on-site forensic investigations.
6. Industrial Applications
   - Real-time process monitoring (Process Analytical Technology, PAT) using spectroscopic green methods.
   - Quality control in cosmetics, polymers, and fine chemicals without hazardous waste.
7. Academic & Research Applications
   - Teaching sustainable analytical practices.
   - Development of computational and chemometric tools for greener method validation.

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