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Review Article

Green Analytical Chemistry: A Comprehensive Review of Eco-Scale, Greenness Metrics, and Sustainability Approaches

Tadikonda Rama Rao *, Afreen, Battula Srilaxmi

Department of Pharmaceutical Analysis, CMR College of Pharmacy, Kandlakoya, Medchal, Hyderabad, 501401

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*Address for Correspondence:

Tadikonda Rama Rao, Department of Pharmaceutical Analysis, CMR College of Pharmacy, Kandlakoya, Medchal, Hyderabad, 501401

Abstract

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 12 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.

Keywords: Green chemistry, National environmental method index, Eco-scale assessment, Green analytical procedure index.

1. Introduction

The topic of green organic synthesis in several chemical industry sectors, particularly the pharmaceutical sector, dominated the early days of green chemistry. In 2000, green chemistry gave rise to green analytical chemistry (GAC).

A list of 12 guiding principles that will be essential to GAC's future is presented in this article. Along with certain well-known concepts (such as cutting back on energy and reagent consumption and getting rid of waste, risk, and hazard), these principles also include some novel ones (such as employing natural reagents). Environmental and human safety in analytical processes is the aim of green analytical chemistry.

"Green Chemistry" can be defined as "the design of chemical products and processes that are more environmentally benign". Some of the Green Chemistry principles can directly be adapted to the analytical chemistry. There are some Green Chemistry concepts that are directly applicable to analytical chemistry. Two approaches can be taken to the link between analytical chemistry and green chemistry. Green chemistry is regulated and supported by analytical chemistry. In this situation, analytical chemistry can be a useful technique for confirming the environmentally friendly outcome of a chemical product or technology. However, chemical analysis techniques produce waste and need energy, reagents, and solvents. The green chemistry concepts proposed by Anastas and Warner[1,2]. The topic of green organic synthesis in several chemical industry sectors, particularly the pharmaceutical sector, dominated the early days of green chemistry. In 2000, green chemistry gave rise to green analytical chemistry (GAC)[3].

Developed the 12 green chemistry tenets. Only a few of these ideas are directly applicable to analytical chemistry; the majority were developed to satisfy the demands of synthetic chemistry. The following principles are used in both synthetic and analytical contexts:

(i) Prevention of waste (principle number 1);

(ii) Safer solvents and auxiliaries (principle number 5);

(iii) Design for energy efficiency (principle number 6); and,

(iv) Reduction of derivatization (principle number 8).

Efforts were also made to find analytical consequences of the 12 principles of green chemistry[4].

2. The 12 Principles of GAC

“GREEN ANALYTICAL CHEMISTRY”

In our approach, the 12 principles of GAC are as follows:

The 12 principles of GAC

1. Direct analytical techniques should be applied to avoid Sample treatment.
2. Minimal sample size and minimal number of samples are Goals.
3. In situ measurements should be performed.
4. Integration of analytical processes and operations saves energy and reduces the use of reagents.
5. Automated and miniaturized methods should be selected.
6. Derivatization should be avoided.
7. Generation of a large volume of analytical waste should be avoided and proper management of analytical waste should Be provided.
8. Multi-analyte or multi-parameter methods are preferred versus methods using one analyte at a time.
9. The use of energy should be minimized.
10. Reagents obtained from renewable source should be preferred.
11. Toxic reagents should be eliminated or replaced.
12. The safety of the operator should be increased.

The idea of the mnemonic of the condensed 24 principles of green Chemistry and green engineering ‘‘IMPROVEMENTS PRODUCTIVELY’’[5,6].

2.1 Significant Events in Green Analytical Chemistry

Three strategies have been developed to lessen the negative environmental effects of analytical techniques.

i) reduction of the number of solvents required in sample pre-treatment;

ii) reduction in the amount and the toxicity of solvents and reagents employed in the measurement step, especially by automation and miniaturization.

iii) development of alternative direct analytical methodologies not requiring solvents or reagents

3) The 10 guidelines for preparing green samples

The GSP approach offers precise and practical instructions for the thorough and methodical enhancement of sample preparation techniques’ and, eventually, analytical techniques’ greenness. The GSP technique is based on sample preparation, which is the primary distinction between it and the GAC principles [7].

The ten principles of Green Sample Preparation:

1. Favour in situ sample preparation
2. Use safer solvents and reagents
3. Target sustainable, reusable, and renewable materials
4. Minimize waste
5. Minimize sample, chemical and material amounts
6. Maximize sample throughput
7. Integrate steps and promote automation
8. Minimize energy consumption
9. Choose the greenest possible post-sample preparation configuration for analysis.
10. Ensure safe procedures for the operator.

4) The key components of green analysis – Basis of GAC principles

Numerous methods and tools are available in modern analytical chemistry to determine a particular analyte in various samples. The main objectives of greening analytical techniques:

I. Reducing or eliminating the use of chemicals (such as reagents, solvents, preservatives, and additions for pH correction);

II. Consuming less energy;

III. Managing analytical waste properly and;

IV. Improving operator safety.

The majority of these problems (such as sample size, energy, waste, danger, and hazard) call for reductions [8].

4.1 SAMPLING

Sampling is the first step in all analysis, with the exception of direct analytical techniques. The second GAC principle states that there should be as few samples as possible, regardless of size. Given how quickly the sampling approach can be changed, this idea is especially crucial for analyzing environmental samples. There are two ways to cut down on the number of samples. In the first, non-invasive procedures such various geophysical approaches (including remote sensing, seismic, and magnetic surveys) are used[9], or devices (like portable XRFs)[10,11] for the purpose of field screening and choosing sampling locations for an in-depth chemical analysis. The second is choosing sampling locations based on statistics to get as much data as possible for accurate result interpretation with a small sample size. One example could be a barbell cluster ANOVA design[12]. Miniaturized analytical techniques[13] or alternative sample introduction Technologies (such as laser ablation of solid samples by LAICP-MS) can be used to reduce the sample size. It is important to carefully consider the potential loss of sample representativeness when reducing the number and volume of samples, particularly when sampling heterogeneous materials[14].

4.2 Experimental Methods

The green analytical procedure index (GAPI), the analytical eco-scale assessment (ESA) approach, and the national environmental method index (NEMI).

The three greenness assessment tools are briefly described here.

1) NEMI or National Environmental Method Index

The Methods and Data Comparability Board (MDCB) is responsible for industrializing this instrument. Its ecological analytical database is the largest. For environmental techniques, the NEMI offers free database access via www.nemi.gov (accessed on February 14, 2021). Keith et al. provided a thorough description of this tool in 2007[15]. As seen in **Figure 1**, the NEMI is represented by a circle known as the greenness profile, which is split into four equal portions. PBT, which stands for persistent, bio accumulative, and toxic, is represented by the first half of the circle. The risky element is expressed in the second section. The corrosiveness and waste are expressed in the third and fourth sections, respectively. Each component can either be coloured green to represent the method's greenness or blank to represent its lack of greenness. Numerous significant elements are taken into account by the greenness profile, including waste volume, pH, and substances with particular qualities. Subsequently, the analyst can assess the degree of eco-friendliness and greenness of various analytical approaches by visually comparing them[16].

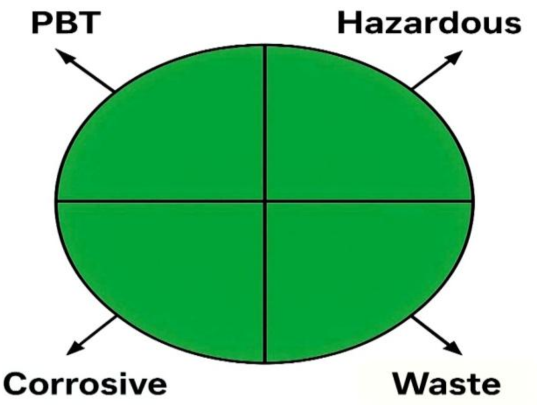

Figure 1: Pictogram of an ideal green analytical method assessed by NEMI tool

2) Analytical Eco-Scale Assessment (ESA)

This metric is based on total points, which may indicate how environmentally friendly the analytical process was. starting with 100 points, which is the highest number. ecologically friendly degree without any penalties), by emphasizing the adverse effects of excipients and additives, like hazardous solvents used in a process, as well as the consequences A penalty point reduces the final score based on the energy and environmental factors. **Figure 2**, If the final score is more than 75 points, the strategy is considered green; nevertheless, if the final score falls between 50 and 75 points, the approach is considered acceptable. The green analytical technique is deemed inadequate if the score is less than 50. The following formula is used to calculate hazard penalty points: Zero penalty points and the absence of a pictogram indicate a non-hazardous chemical, one penalty point is awarded for a less serious hazardous chemical.

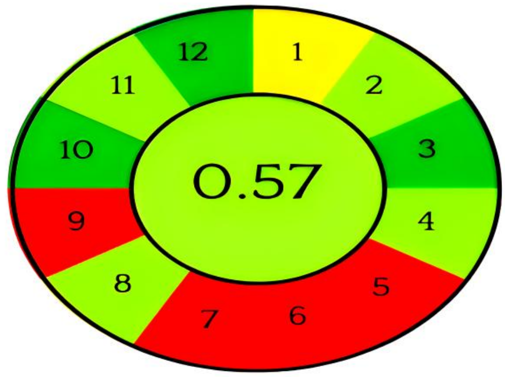

Figure 2: An ideal green analytical method assessed by ESA tool

3) Green Analytical Procedure Index (GAPI)

This is a novel tool that J. Potka-Wasylka introduced in 2018[17], that can evaluate the environmental friendliness of an analytical process from sample collection to the end result. According to the GAPI, every analytical procedure starts with sample collection, which is followed by a second phase that protects the sample from damaging chemical and physical changes. The third and last step then uses analytical methods to determine and quantify it. The GAPI tool includes a pictogram that classifies the ecological value of each analytical process step using a colour pattern (green, yellow, and red).

4) The Analytical Greenness calculator (AGREE)

AGREE is a thorough, adaptable, and uncomplicated assessment method that yields a result that is simple to understand and educational. The factors taken into consideration in AGREE are derived from the 12 GAC principles and converted into a single 0–1 scale**,** one benefit of this metric is that freeware software is readily available making its applications simpler[18].

CONCLUSION

New insights on measures that enable the assessment of the analytical processes are needed as interest in green analytical chemistry grows. GAC metrics offer the chance to. compare various analytical method parameters and steps in order to identify the less environmentally friendly elements that might be further enhanced to satisfy 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. 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.

ABBREVIATION

NEMI: National environmental methods index, MDCB: methods and data comparability, ESA: eco-scale assessment, GAPI: green analytical procedure index, PBT: persistent, bio accumulative, and toxic, GAC: green analytical chemistry.

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Author's Contribution: The authors of this comprehensive review have made significant contributions to the field of green analytical chemistry. Their work includes[2]:

Conceptualization: Developing the concept of green analytical chemistry and its importance in sustainable growth.

Methodology: Establishing metrics and tools to assess the greenness of analytical methods.

Investigation: Conducting research on eco-scale, greenness metrics, and sustainability approaches.

Writing and Editing: Preparing and revising the manuscript for publication.

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Ethical Approvals: This study does not involve experiments on animals or human subjects.

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