

Comprehensive Review of Greenness, Whiteness, And Blueness Assessments of Analytical Methods

Pakir Pranaya¹, Prof. Kumaraswamy Gandla², Lalitha Repudi³

¹*Research Scholar, Department of Pharmacy, Chaitanya (Deemed to be University), Gandipet, Himayath Nagar (Vil), Hyderabad, Telangana, India-500075*

^{2,3}*Department of Pharmacy, Chaitanya (Deemed to be University), Gandipet, Himayath Nagar (Vil), Hyderabad, Telangana, India-500075*

Abstract—Green Analytical Chemistry (GAC) has emerged as an important approach for reducing the environmental and occupational impacts associated with analytical measurements while maintaining analytical quality and reliability. Conventional analytical procedures may involve large quantities of organic solvents, hazardous reagents, energy-intensive instrumentation, extensive sample preparation, and generation of considerable chemical waste. To address these challenges, numerous assessment tools have been developed to characterize the greenness of analytical procedures, including the National Environmental Methods Index (NEMI), Analytical Eco-Scale, Green Analytical Procedure Index (GAPI), Analytical Greenness metric (AGREE), and AGREE prep. Although these tools provide valuable information about environmental performance, greenness alone does not necessarily indicate whether an analytical method is accurate, precise, robust, economical, rapid, and suitable for routine application. White Analytical Chemistry (WAC) was therefore proposed as a more holistic concept integrating three complementary dimensions: analytical performance or “redness,” environmental sustainability or “greenness,” and practical applicability or “blueness.” The Blue Applicability Grade Index (BAGI) subsequently provided a dedicated approach for evaluating the practical aspects of analytical methods. This brief review summarizes the principles, characteristics, advantages, limitations, and complementary roles of green, white, and blue assessment approaches and proposes an integrated framework for selecting sustainable, reliable, and practically applicable analytical methods.

Index Terms—Green Analytical Chemistry; White Analytical Chemistry; Greenness; Whiteness; Blueness; GAPI; AGREE; AGREE prep; RGB model; BAGI; Analytical Method Assessment; Sustainability.

I. INTRODUCTION

Analytical chemistry plays an essential role in pharmaceutical quality control, clinical analysis, environmental monitoring, food safety, forensic science, and industrial research. However, analytical procedures themselves can generate environmental burdens through solvent and reagent consumption, waste generation, energy requirements, hazardous chemicals, and complex sample-preparation procedures. Green Analytical Chemistry (GAC) aims to minimize these impacts while preserving the required analytical performance [1,2].

The development of the twelve principles of Green Analytical Chemistry provided a conceptual basis for designing safer, more efficient, and environmentally responsible analytical procedures [2]. Subsequently, several metrics were introduced to evaluate the environmental performance of analytical methods. NEMI provided an early visual assessment, while the Analytical Eco-Scale introduced a penalty-point approach. GAPI expanded assessment to the entire analytical procedure, whereas AGREE incorporated the twelve principles of GAC into a unified numerical score. AGREE prep further emphasized the environmental performance of sample preparation [3–7].

Despite these advances, an analytical method with excellent environmental performance may not necessarily be the best method for routine laboratory use. Analytical characteristics such as accuracy, precision, selectivity, sensitivity, robustness, analysis time, throughput, cost, automation, instrumentation requirements, and operational simplicity must also be considered. White Analytical Chemistry (WAC) was

introduced to address this broader perspective by combining analytical performance, environmental impact, and practical feasibility using the red–green–blue (RGB) concept [8].

More recently, the Blue Applicability Grade Index (BAGI) was developed specifically to assess the practical applicability of analytical methods [9]. Consequently, contemporary method evaluation increasingly favors a multidimensional approach rather than relying on a single greenness metric.

II. EVOLUTION OF ANALYTICAL METHOD ASSESSMENT

The evolution of analytical method assessment can be represented as a transition from environmental protection → quantitative greenness → holistic sustainability.

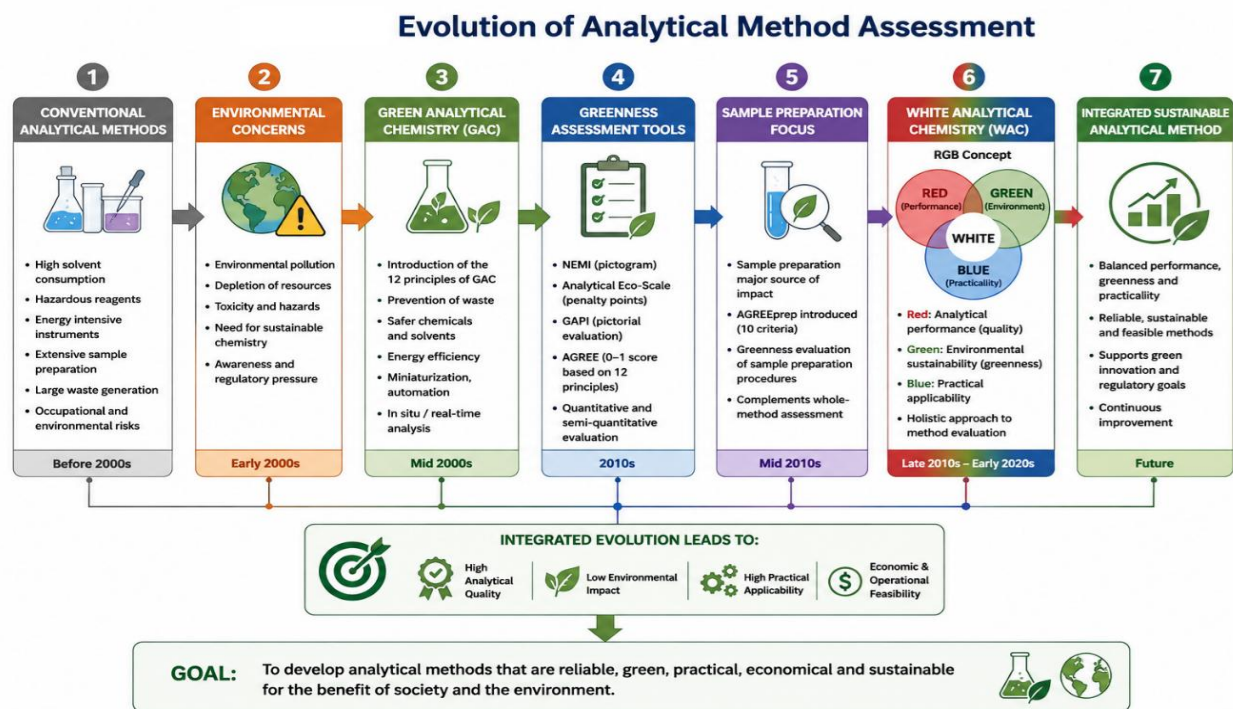


Figure 1. Evolution of analytical method assessment

CONVENTIONAL ANALYTICAL METHODS

↓

Environmental concerns
Solvent consumption • Hazardous reagents
Waste generation • Energy consumption

↓

GREEN ANALYTICAL CHEMISTRY

↓

Greenness assessment
NEMI → Eco-Scale → GAPI → AGREE

↓

Sample-preparation assessment

AGREEprep

↓

WHITE ANALYTICAL CHEMISTRY

↓

RED GREEN BLUE
Performance Environment Practicality

↓

Integrated sustainable analytical method
GAPI evaluates the entire analytical procedure from sample collection through final determination, whereas AGREE translates the twelve GAC principles into a normalized 0–1 score.

III. GREENNESS ASSESSMENT OF ANALYTICAL METHODS

3.1. National Environmental Methods Index (NEMI)
NEMI is one of the earliest approaches used to provide a rapid visual assessment of analytical methods. It employs a four-quadrant pictogram based primarily on persistence, bioaccumulation and toxicity (PBT), hazardous substances, corrosivity, and waste-related considerations.

Advantages:

- Simple and rapid.
- Easy visual interpretation.
- Useful for comparison of established analytical procedures.

Limitations:

- Primarily qualitative.
- Does not provide a comprehensive numerical score.
- May not adequately represent energy consumption, sample preparation, or method performance.

Thus, NEMI is useful as an initial screening tool but is generally insufficient as a stand-alone assessment for complex modern analytical procedures.

3.2. Analytical Eco-Scale

The Analytical Eco-Scale was introduced as a semi-quantitative approach based on penalty points. An ideal analytical procedure is assigned a score of 100, and penalty points are subtracted according to factors such as reagent hazards, solvent consumption, energy requirements, occupational hazards, and waste generation [3].

Figure 2. Analytical Eco-Scale Concept

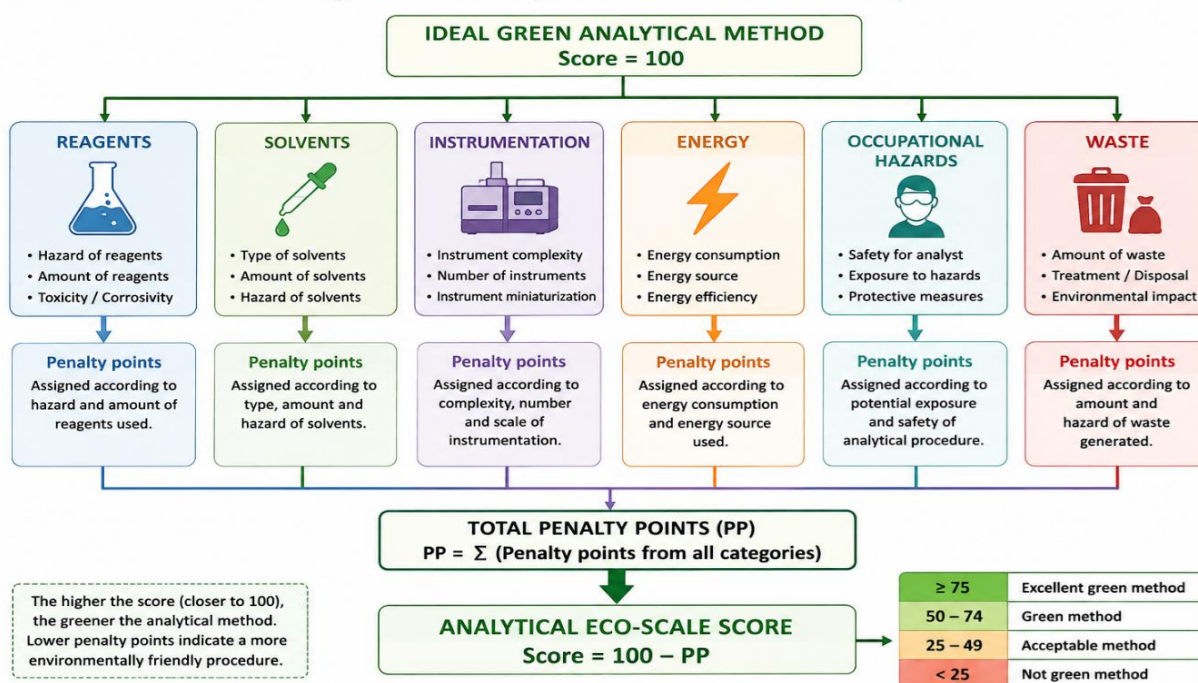
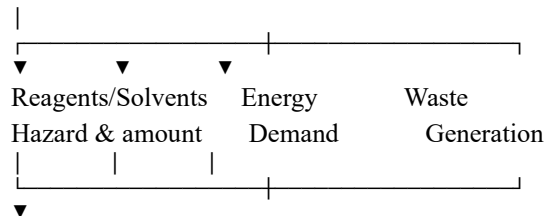


Figure 2. Analytical Eco-Scale concept

IDEAL GREEN ANALYSIS

Score = 100



PENALTY POINTS

↓
Eco-Scale = 100 - Penalty Points

The principal advantage of the Eco-Scale is its numerical interpretation, allowing methods to be compared more readily than with purely qualitative approaches.

3.3. Green Analytical Procedure Index (GAPI)

GAPI was developed to provide a comprehensive pictorial evaluation of the entire analytical procedure. It considers multiple stages, including sample collection, preservation, preparation, extraction, separation, detection, reagents, solvents, energy, and waste.

Different colours indicate over, intermediate, or higher environmental impact [4].

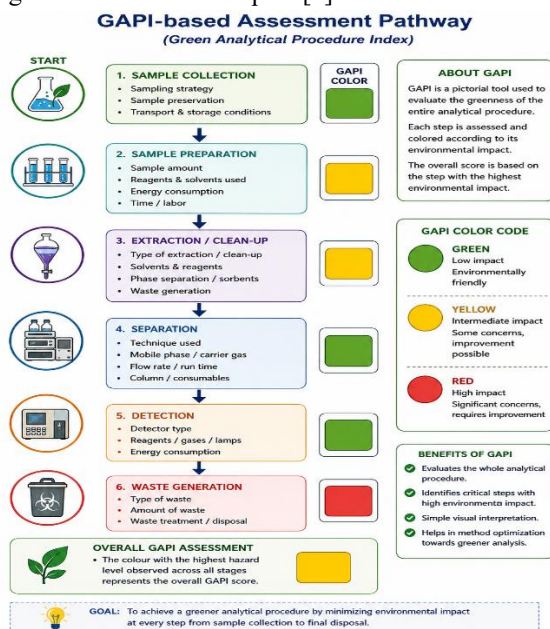
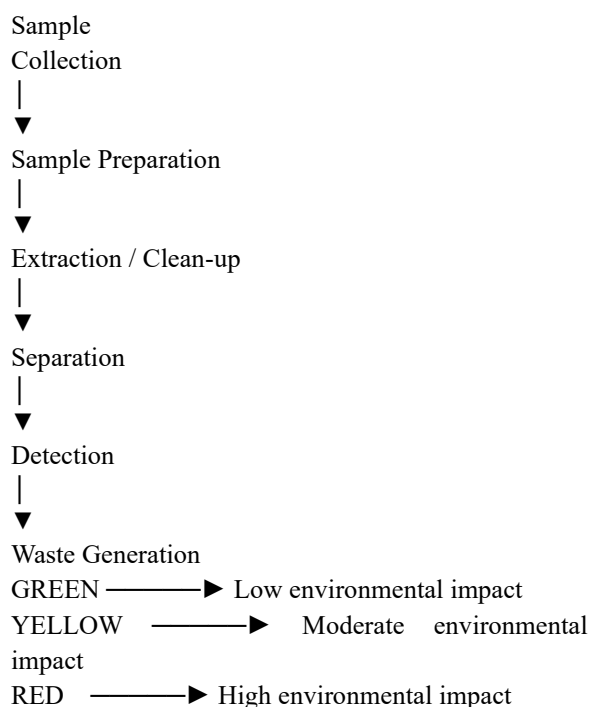


Figure 3. GAPI-based assessment pathway



GAPI is particularly valuable because it highlights the weak points of an analytical procedure, rather than providing only one overall score.

3.4. Analytical GREEnness Metric (AGREE)

AGREE was introduced to provide a comprehensive numerical assessment based on the twelve principles of GAC. Each principle is evaluated and transformed into a unified 0–1 scale, with the final result presented through a characteristic pictogram.

A higher score indicates better alignment with the principles of green analytical chemistry [5].

AGREE incorporates factors such as:

- Waste prevention;
- Safer chemicals;
- Safer solvents;
- Energy efficiency;
- Sample reduction;
- Reduced sample preparation;
- Automation and miniaturization;
- In situ and real-time analysis;
- Multi-analyte analysis; and
- Reduction of occupational hazards.

The major advantage of AGREE is that it combines multiple GAC principles into an easily interpretable overall score while retaining information about individual criteria.

3.5. AGREE prep

Sample preparation can represent a major source of environmental impact because of solvent use, extraction steps, reagents, energy requirements, and waste generation.

AGREEprep was introduced specifically to assess the greenness of sample-preparation procedures using ten assessment criteria related to the principles of green sample preparation [6].

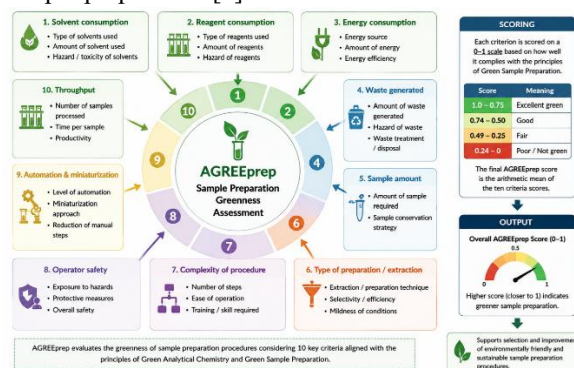
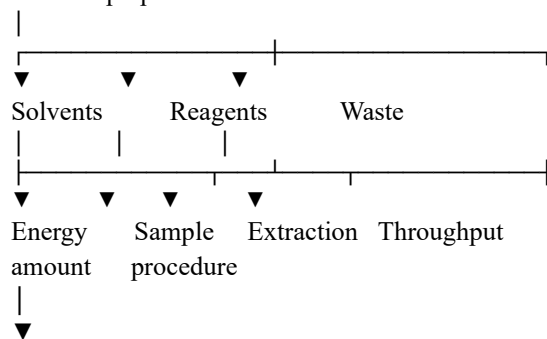


Figure 4. AGREE prep assessment framework

AGREE prep



Overall score (0–1)

AGREE prep therefore complements whole-method tools by providing greater resolution of the sample-preparation component.

IV. WHITE ANALYTICAL CHEMISTRY

Greenness assessment focuses mainly on environmental impact. However, analytical method

selection requires consideration of additional dimensions. A highly green procedure may have poor sensitivity, low precision, inadequate selectivity, long analysis time, high cost, or poor suitability for routine laboratories.

To overcome this limitation, Nowak and co-workers introduced the concept of White Analytical Chemistry (WAC). WAC integrates three major dimensions:

- Red: analytical performance;
- Green: environmental sustainability;
- Blue: practical and economic applicability.

The RGB concept is analogous to additive color mixing, in which red, green, and blue components combine to produce white. In analytical chemistry, a “white” method represents a balance among analytical quality, environmental responsibility, and practical feasibility [8].

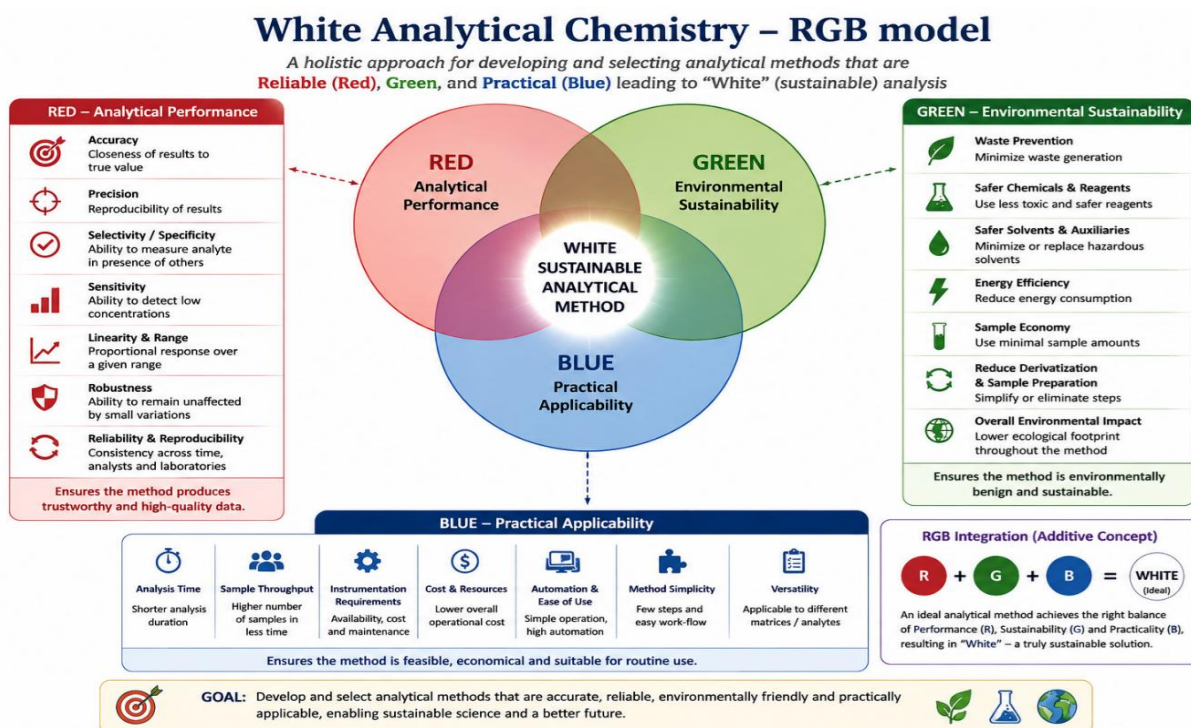
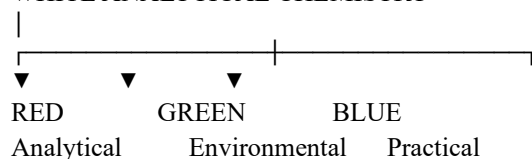


Figure 5. White Analytical Chemistry – RGB model

WHITE ANALYTICAL CHEMISTRY



performance

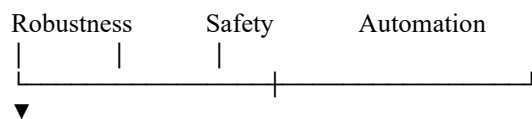
Accuracy
Precision
Selectivity
Sensitivity

sustainability

Waste
Solvents
Hazards
Energy

applicability

Cost
Time
Throughput
Equipment



WHITENESS / WAC

The WAC concept emphasizes that sustainability should not be achieved at the expense of analytical reliability or practical functionality.

V. REDNESS: ANALYTICAL PERFORMANCE

The “red” component represents the analytical performance of a method. Important characteristics include accuracy, precision, selectivity, sensitivity,

linearity, detection limit, quantification limit, robustness, reproducibility, and reliability.

A method cannot be considered truly sustainable if it produces unreliable analytical results. For example, replacing a conventional chromatographic solvent with a greener solvent may improve the environmental score but could adversely affect chromatographic resolution or sensitivity.

Consequently, environmental improvement must be balanced against analytical performance.

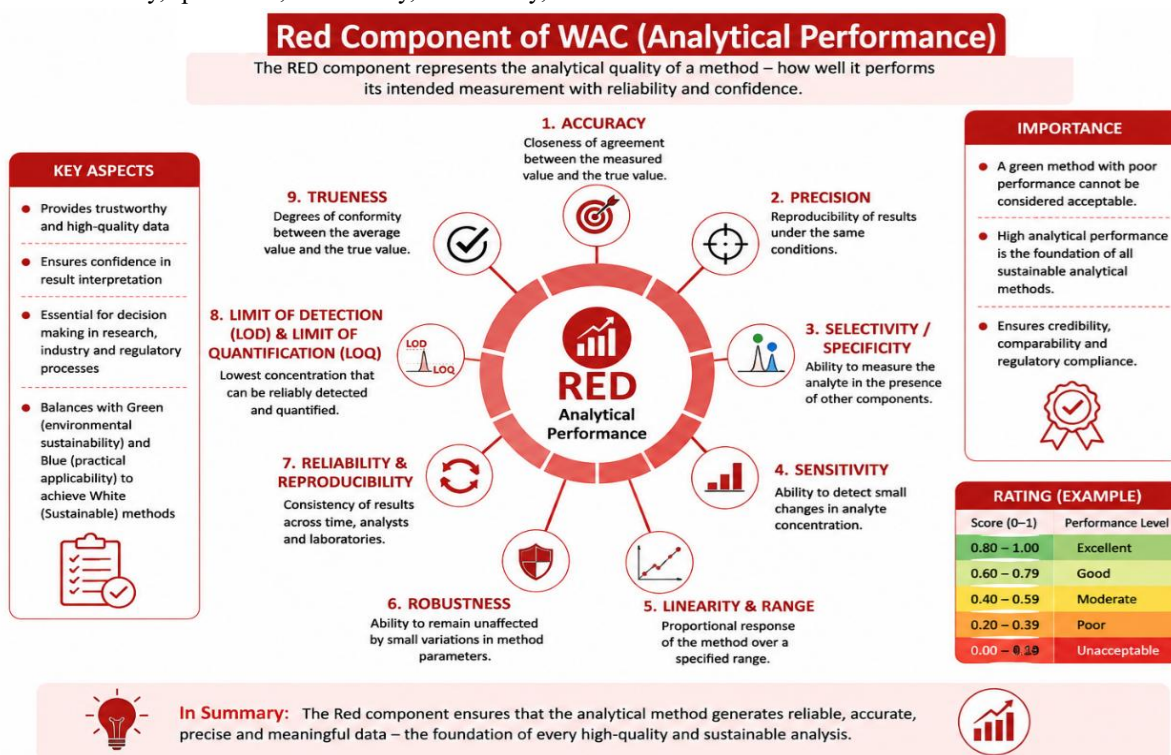
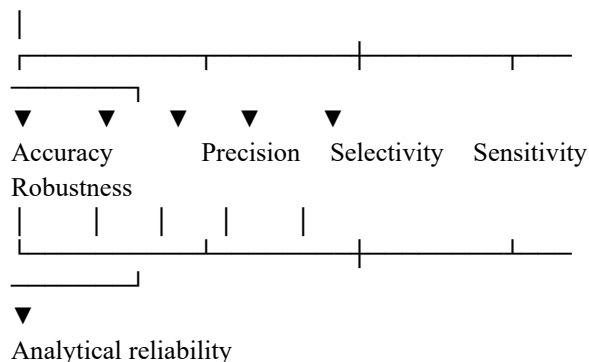


Figure 6. Red component of WAC

ANALYTICAL PERFORMANCE



VI. BLUENESS: PRACTICAL APPLICABILITY

The blue component addresses whether a method can realistically be implemented in research, industrial, regulatory, or routine analytical laboratories.

Important blue characteristics include:

- Analysis time;
- Sample throughput;
- Instrumentation requirements;
- Automation;

- Sample-preparation complexity;
- Number of analytes;
- Sample quantity;
- Reagent and material requirements;
- Preconcentration requirements;
- Operational simplicity; and
- Economic feasibility.

6.1. Blue Applicability Grade Index (BAGI)

BAGI was introduced as a dedicated metric for evaluating the practical applicability of analytical methods. It evaluates ten main attributes and generates

an asteroid-shaped pictogram together with a numerical score.

The tool was specifically designed to complement green metrics and address practical aspects of WAC [9].

The ten attributes include the type of analysis, number of simultaneously determined analytes, sample throughput, reagents/materials, instrumentation, simultaneous sample treatment, preconcentration requirements, automation, sample preparation, and sample amount [9].

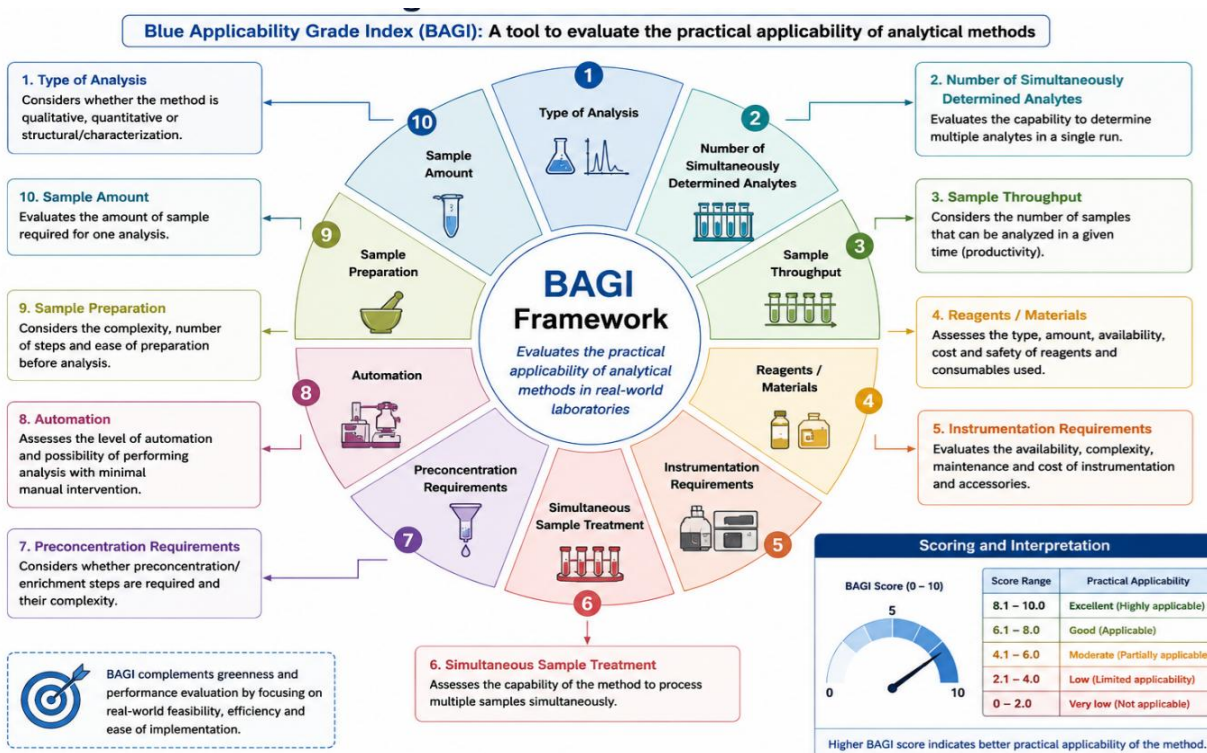
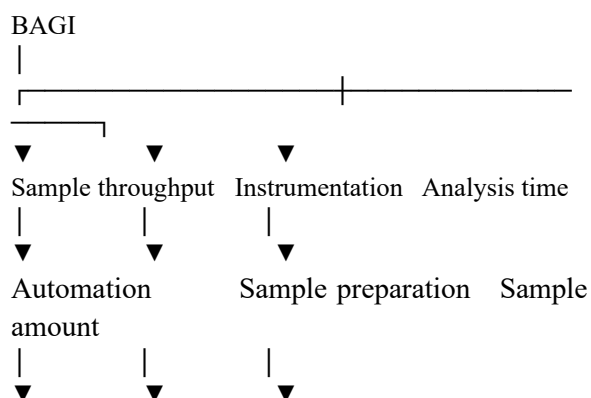


Figure 7. BAGI framework



Reagents/materials Preconcentration Multi-analyte capability

PRACTICAL APPLICABILITY

BAGI uses a blue color scale and provides both a visual pictogram and a numerical score. A score above 60 has been suggested as an indication of practical applicability in the original BAGI framework [9].

VII. COMPARATIVE EVALUATION OF GREENNESS, WHITENESS AND BLUENESS

Table 1. Major analytical assessment approaches

Assessment	Main objective	Major parameters	Typical output
NEMI	Environmental screening	Hazard, PBT, corrosivity, waste	Pictogram
Eco-Scale	Semi-quantitative greenness	Reagents, solvents, energy, waste	Score / 100
GAPI	Whole analytical procedure	Sample collection to detection	Color pictogram
AGREE	Overall greenness	12 GAC principles	Score / 1
AGREE prep	Sample-preparation greenness	Solvent, waste, energy, sample, throughput	Score / 1
RGB/WAC	Holistic method quality	Red + Green + Blue	Whiteness/RGB assessment
BAGI	Practical applicability	Throughput, time, equipment, automation, etc.	Score + blue pictogram

VIII. ADVANTAGES AND LIMITATIONS

No individual assessment tool can fully describe all aspects of an analytical procedure.

Table 2. Advantages and limitations of major approaches

Tool	Advantages	Limitations	Tool
NEMI	Simple, rapid, visual	Mainly qualitative	NEMI
Eco-Scale	Numerical, relatively simple	Some criteria require subjective decisions	Eco-Scale
GAPI	Whole-procedure visualization	More complex than NEMI	GAPI
AGREE	Comprehensive, quantitative	Requires more input data	AGREE
AGREEprep	Detailed sample-preparation assessment	Limited to sample preparation	AGREEprep
RGB/WAC	Integrates performance, environment and practicality	Assessment can require multiple datasets	RGB/WAC
BAGI	Dedicated practicality assessment	Does not replace environmental or validation assessment	BAGI

IX. INTEGRATED ASSESSMENT STRATEGY

The most appropriate approach is not necessarily to select one metric but to combine complementary metrics according to the objective of the study.

For a newly developed pharmaceutical analytical method, for example, the following sequence can be adopted:

- Step 1: Validate analytical performance.
- Step 2: Evaluate environmental performance using GAPI, AGREE, Eco-Scale, or an appropriate complementary tool.
- Step 3: Evaluate sample preparation using AGREE prep when sample treatment is significant.
- Step 4: Evaluate practical applicability using BAGI.
- Step 5: Compare competing analytical methods using the same assessment framework.

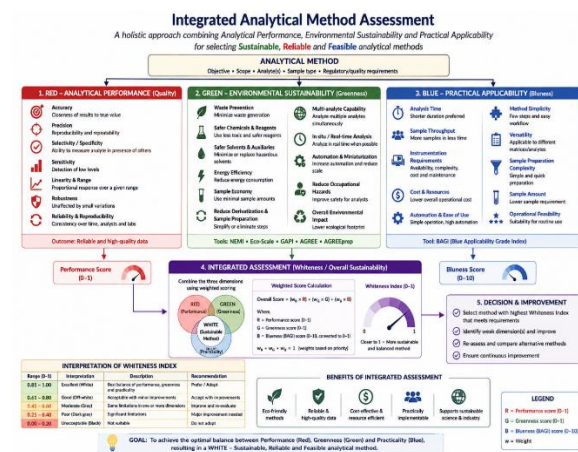
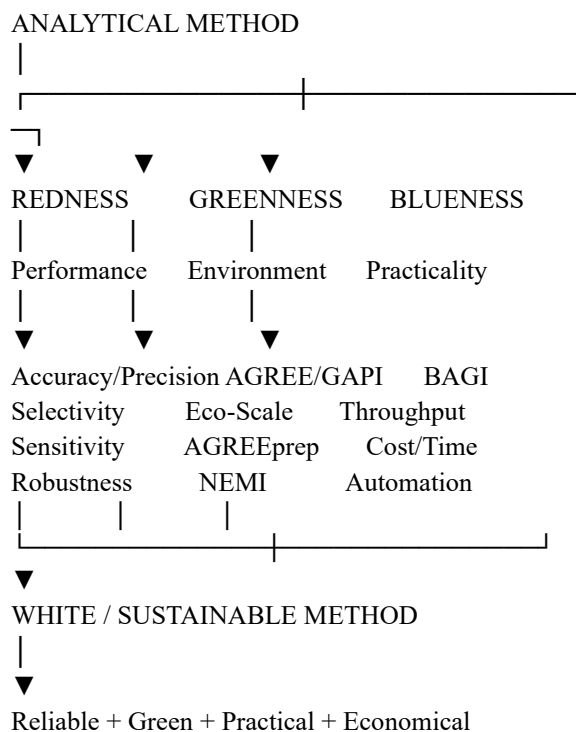


Figure 8. Integrated analytical method assessment



X. FUTURE PERSPECTIVES

The future of analytical method assessment is likely to move toward increasingly integrated, data-driven, and automated evaluation. Recent developments include simplified RGB-based approaches such as RGBfast, which aims to reduce the complexity of comprehensive greenness and whiteness evaluation [10].

Digital analytical platforms, artificial intelligence, automation, miniaturized instrumentation, microfluidics, remote sensing, direct analysis, and real-time monitoring may further reduce solvent consumption, waste generation, sample requirements, and energy consumption.

Future assessment frameworks should also improve:

1. Standardization of scoring systems;
2. Transparency of weighting factors;
3. Assessment of carbon footprint and energy consumption;
4. Incorporation of sample preparation;
5. Consideration of analytical performance;
6. Economic and operational feasibility;
7. Life-cycle thinking; and
8. Automated comparison of multiple analytical methods.

A particularly promising direction is the integration of green, red, and blue indicators into a unified decision-support system, enabling researchers to identify methods that are not only environmentally preferable but also analytically reliable and practically implementable.

XI. CONCLUSION

Assessment of analytical methods has progressed from simple environmental screening toward comprehensive sustainability evaluation. Greenness tools such as NEMI, Analytical Eco-Scale, GAPI, AGREE, and AGREEprep provide valuable information about environmental impact, solvent consumption, waste generation, hazards, energy requirements, and sample preparation. However, environmental performance alone cannot determine the overall suitability of an analytical method.

The concept of White Analytical Chemistry provides a broader framework by integrating analytical performance (redness), environmental sustainability (greenness), and practical applicability (blueness). BAGI offers a dedicated approach for quantifying the practical dimension of analytical methods. Therefore, combining complementary tools rather than relying on a single metric can provide a more balanced evaluation.

The future of analytical chemistry should move toward methods that are green, analytically robust, practical, economical, safe, and sustainable. The integration of GAC and WAC concepts with digital technologies and automated assessment tools is expected to facilitate rational selection and development of next-generation analytical methods.

REFERENCES

- [1] S. Armenta, S. Garrigues, and M. de la Guardia, "Green analytical chemistry," *TrAC Trends in Analytical Chemistry*, vol. 27, pp. 497–511, 2008, doi: 10.1016/j.trac.2008.05.003.
- [2] A. Gałuszka, Z. M. Migaszewski, and J. Namieśnik, "The 12 principles of green analytical chemistry and the SIGNIFICANCE mnemonic of green analytical practices," *TrAC Trends in Analytical Chemistry*, vol. 50, pp. 78–84, 2013, doi: 10.1016/j.trac.2013.04.010.

- [3] A. Gałuszka, Z. M. Migaszewski, P. Konieczka, and J. Namieśnik, "Analytical Eco-Scale for assessing the greenness of analytical procedures," *TrAC Trends in Analytical Chemistry*, vol. 37, pp. 61–72, 2012, doi: 10.1016/j.trac.2012.03.013.
- [4] J. Płotka-Wasyłka, "A new tool for the evaluation of the analytical procedure: Green Analytical Procedure Index," *Talanta*, vol. 181, pp. 204–209, 2018, doi: 10.1016/j.talanta.2018.01.013.
- [5] F. Pena-Pereira, W. Wojnowski, and M. Tobiszewski, "AGREE—Analytical GREENness Metric Approach and Software," *Analytical Chemistry*, vol. 92, pp. 10076–10082, 2020, doi: 10.1021/acs.analchem.0c01887.
- [6] W. Wojnowski, M. Tobiszewski, F. Pena-Pereira, and E. Psillakis, "AGREEprep—Analytical greenness metric for sample preparation," *TrAC Trends in Analytical Chemistry*, vol. 149, Art. no. 116553, 2022, doi: 10.1016/j.trac.2022.116553.
- [7] F. Pena-Pereira, M. Tobiszewski, W. Wojnowski, and E. Psillakis, "A tutorial on AGREEprep: An analytical greenness metric for sample preparation," *Advances in Sample Preparation*, vol. 3, Art. no. 100025, 2022, doi: 10.1016/j.sampre.2022.100025.
- [8] P. M. Nowak, R. Wietecha-Posłuszny, and J. Pawliszyn, "White Analytical Chemistry: An approach to reconcile the principles of Green Analytical Chemistry and functionality," *TrAC Trends in Analytical Chemistry*, vol. 138, Art. no. 116223, 2021, doi: 10.1016/j.trac.2021.116223.
- [9] N. Manousi, W. Wojnowski, J. Płotka-Wasyłka, and V. Samanidou, "Blue applicability grade index (BAGI) and software: A new tool for the evaluation of method practicality," *Green Chemistry*, vol. 25, pp. 7598–7604, 2023, doi: 10.1039/D3GC02347H.
- [10] P. M. Nowak and F. Arduini, "RGBfast—A user-friendly version of the Red-Green-Blue model for assessing greenness and whiteness of analytical methods," *Green Analytical Chemistry*, vol. 10, Art. no. 100120, 2024, doi: 10.1016/j.greeac.2024.100120.
- [11] P. M. Nowak, R. Wietecha-Posłuszny, M. Woźniakiewicz, et al., "A perspective of the comprehensive and objective assessment of analytical methods including the greenness and functionality criteria: Application to the determination of zinc in aqueous samples," *Frontiers in Chemistry*, vol. 9, Art. no. 753399, 2021, doi: 10.3389/fchem.2021.753399.
- [12] M. Tobiszewski, "Metrics for green analytical chemistry," *Analytical Methods*, vol. 8, pp. 2993–2999, 2016, doi: 10.1039/C6AY00478D.
- [13] A. I. López-Lorente et al., "The ten principles of green sample preparation," *TrAC Trends in Analytical Chemistry*, vol. 148, Art. no. 116530, 2022.
- [14] S. F. Hammad, M. A. Adel Hamid, L. Adly, and S. H. Elagamy, "Comprehensive review of greenness, whiteness, and blueness assessments of analytical methods," *Green Analytical Chemistry*, vol. 12, Art. no. 100209, 2025, doi: 10.1016/j.greeac.2025.100209.