Original Article

http://www.tjbac.tmu.ac.in

TMU Journal of Basic & Applied Chemistry

Jan-December, 2025: P.63-68

Green Chemistry and Forensic Science: Towards Sustainable Forensic Analysis

Abstract

Forensic science makes extensive use of analytical chemistry to locate and examine evidence. Conventional forensic science techniques may involve hazardous chemicals and solvents, high energy consumption, laborious sample preparation, and substantial chemical waste. While preserving the accuracy of the analysis, green chemistry can help reduce these negative consequences for the environment and human health. Greener analytical techniques, such as cleaner solvents, microscale sample preparation, reduced reagent use, energy-efficient apparatus, and non-destructive analysis, have been produced by combining green chemistry and forensic science. The significance of the twelve green chemistry principles—waste prevention, sample and solvent minimisation, green extraction, safe analytical reagents, and energy efficiency—in forensic science will be discussed in this paper. Toxicology, confiscated narcotics, questioned documents, trace evidence, explosives, and environmental forensics have all been highlighted as forensic applications. The sustainability of forensic methods can be evaluated using several analytical greenness evaluation tools, including the Analytical Eco-Scale, the Green Analytical Procedure Index (GAPI), the Complex GAPI, and AGREE. Green chemistry offers an intriguing approach to creating a sustainable forensic lab, even though challenges remain in technique validation, sensitivity, standardisation, and laboratory infrastructure.

Gandharve Kumar

Author Affiliations

Gandharve Kumar

Chemistry Department & Sustainability,

School of Basic Sciences, Galgotias University,

Greater Noida- 203201, India.

***Corresponding Author**

Gandharve Kumar

Chemistry Department & Sustainability,

School of Basic Sciences, Galgotias University,

Greater Noida- 203201, India.

E- mail: gandharve.kumar@galgotiasuniversity.edu.in

Received on: 01.08.2026

Revised on: 12.08.2026

Accepted on: 17.08.2026

Keywords: Green chemistry; forensic science; green analytical chemistry; green sample preparation; forensic toxicology; safer solvents; sustainable analysis; analytical greenness.

1. Introduction

The application of scientific methods to the analysis and interpretation of evidence for criminal investigations is known as forensic science [1]. Forensic toxicology, drug analysis, document examination, trace evidence analysis, fire debris analysis, explosives analysis, and forensic environmental research all depend heavily on chemistry [2]. Numerous methods are frequently employed, such as GC-MS, LC-MS, HPLC, FTIR, Raman spectroscopy, XRF, and atomic spectroscopy. Traditional procedures use a large amount of chemicals and organic solvents, even though these methods provide highly accurate analytical results [3]. Extraction, purification, concentration, derivatisation, and chromatographic separations are energy-intensive processes that produce hazardous waste. The main goal of green chemistry is to prevent pollution by enabling safer, more efficient chemical reactions [4]. Green Analytical Chemistry (GAC), which seeks to obtain analytical results using less sample, fewer reagents and solvents, less energy, and less waste, can also be applied to the discipline of analytical chemistry. Because the evidence in these situations may be extremely scarce and irreplaceable, the use of green chemistry in forensic science becomes even more crucial [5].

2. Principles of Green Chemistry Pertinent to Forensic Science

The Twelve Principles of Green Chemistry offer guidance for developing analytical methods that respect the environment. The following lists the significance of these concepts for forensic laboratories [6].

2.1 Preventing Waste

The production of hazardous waste must be restricted, not controlled after production. Waste can be decreased through automation, direct analysis, microscale extraction, and reduced reaction volumes.

2.2 Safer Reagents and Solvents

When analytically feasible, safer substances such as water, ethanol, and ethyl acetate should be used in place of hazardous solvents. Toxicity, volatility, biodegradability, flammability, and analytical efficiency will all be considered when choosing solvents.

2.3 Decrease in Sample and Reagent Usage

There is very little forensic evidence available. While maintaining sufficient sensitivity for analysis, the use of microextraction and sample preparation minimises loss of samples and reagents.

2.4 Efficiency of Energy

Avoiding heating, cooling, evaporation, and prolonged instrument operation is crucial. Energy-saving devices, direct analysis, portable equipment, and faster chromatography could all contribute to energy conservation.

2.5 Avoiding Derivatisation

As we can see, derivatisation results in additional operations, waste, and reagents. When determining compounds, it is best to use an analytical method that does not require derivatisation.

2.6 Secure Analytical Techniques

Reagents that are poisonous, corrosive, volatile, reactive, or flammable should be used as little as possible. It is advantageous for both workplace safety and environmental sustainability.

3. Forensic Science and Green Analytical Chemistry

Sustainability considerations are explicitly applied to analytical measures in green analytical chemistry. Accurate, dependable results with low environmental effect are the ultimate goal [8]. Green sample preparation is a crucial strategy. Large amounts of organic solvents may be required for the traditional method of liquid-liquid extraction. Alternative techniques include dispersive microextraction, ultrasound-assisted extraction, microwave-assisted extraction, solid-phase microextraction, liquid-phase microextraction, and solvent-free techniques [9]. Because it reduces the need for solvents and preserves evidence for later use, miniaturisation is particularly helpful in forensic analysis. Miniaturisation, safer solvents, and environmentally friendly sorbents are the main avenues for creating a sustainable forensic analytical method, according to recent studies. Non-destructive analytical methods such as Raman spectroscopy, FTIR, microscopy, and X-ray analysis can further reduce the amount of sample required. The examination of contested papers, fibres, paints, glass, minerals, and other types of trace evidence can benefit greatly from this [10].

4. Applications of Green Chemistry in Forensic Science

4.1 Toxicology for Forensics

Analyzing drugs, metabolites, toxins, and other substances in biological samples is a common task in forensic toxicology. Conventional extraction methods may require a large amount of organic solvents. The amount of sample required and the use of solvents will be reduced by miniaturised extraction, analysis, and LC-MS/MS [11].

4.2 Identification of Seized Drugs

Color tests, extraction, chromatographic separations, and spectroscopic techniques can all be used in drug testing. Rapid, non-destructive screening and subsequent analysis will be possible with a more environmentally friendly drug identification process. Techniques like FTIR, Raman spectroscopy, and portable analytical tools will yield preliminary information without damaging the evidence, allowing it to be further examined.

4.3 Documents Under Question

Extraction and chromatographic separations are typically used in traditional ink and paper analysis. Miniaturisation, cleaner solvents, Raman spectroscopy, FTIR, and digital photography are examples of green techniques. Because the original document is saved and can be used again, non-destructive analysis is particularly beneficial.

4.4 Analysis of Traces

Spectroscopic and microscopic analyzes can typically be used with little sample preparation for analyzing trace materials such fibers, glass, paints, polymers, soils, and cosmetic traces. Therefore, chemical consumption can be decreased without sacrificing evidence preservation using Raman spectroscopy, FTIR, microscopy, and XRF.

4.5 Explosive Evidence and Fire Debris

Mixtures of organic and inorganic materials can be found in explosion remnants and fire debris. Solvent consumption can be reduced by using techniques such as chromatography, headspace analysis, and reduced-volume extraction. However, as forensic analysis necessitates accurate trace detection, more environmentally friendly methods must guaranty adequate recovery and sensitivity.

4.6 Environmental Forensic Analysis

Because forensic environmental analyses are likely to involve numerous samples, there is considerable opportunity to reduce the amount of solvents and reagents used. The environmental impact of forensic analyses can be reduced through automation, direct spectroscopy, and extraction miniaturisation. Because forensic environmental analyses are likely to involve numerous samples, there is considerable opportunity to reduce the amount of solvents and reagents used. The environmental impact of forensic analyses can be reduced through automation, direct spectroscopy, and extraction miniaturisation.

5 Green metrics for forensic analysis

The use of a tiny amount of solvent alone does not qualify an analytical method as "green." It is necessary to take into account the full analysis procedure [12].

5.1 Eco-Scale Analysis

The Analytical Eco-Scale evaluates analytical techniques by assigning points as penalties for undesirable elements such waste, energy consumption, chemical quantities, and the presence of hazardous substances. Greenness is indicated by a higher number.

5.2 Index of Green Analytical Procedures

Sampling, sample preparation, reagents and solvents, instruments, and waste management are all evaluated by the Green Analytical Procedure Index (GAPI). GAPI's graphical format makes it simple to identify stages that are not ecologically friendly.

5.3 AGREE and Complex GAPI

While AGREE evaluates analytical techniques in accordance with the 12 green analytical chemistry principles, the Complex GAPI is intended to thoroughly evaluate analytical processes. Both methods can be used to contrast more environmentally friendly forensic techniques with more conventional ones. A thorough assessment of forensic analytical techniques will be produced by combining green parameters with traditional validation parameters.

6. Green Forensic Chemistry's Benefits

Using green chemistry in forensic investigations has several advantages, including [13]:

- A decrease in the hazardous waste that chemicals produce.
- Staff members are exposed to fewer hazardous materials.
- Use of organic solvents is reduced.
- Aiding in the conservation of forensic evidence, a finite resource.
- Saving resources and energy.
- Simplifying tasks.
- Lower laboratory expenses.
- Non-destructive analysis is used frequently.
- Environmental sustainability in laboratories.

The crucial aspect of green chemistry is that analytical quality is not compromised. The goal is to use the safest, most resource-efficient method to get the forensic outcome.

7. Challenges and Future Prospects

Maintaining forensic dependability while reducing environmental impact will be the greatest difficulty. The new technique must be validated to guarantee robustness, reproducibility, accuracy, precision, sensitivity, selectivity, and recovery. The lack of widely recognised sustainable standards unique to forensics, the expense of new equipment, employee training, laws, and the scarcity of green solvents are further obstacles. Miniaturisation, automation, portable equipment, direct analysis, high-resolution mass spectrometry, contemporary spectroscopy, and data processing aided by artificial intelligence are likely to be the main areas of future advancement. The development of a green forensic analytical platform that combines traditional forensic validation with environmental aspects such as solvent use, waste production, energy consumption, sample usage, and analytical greenness score is one of the most promising fields [14].

8. Conclusion

A helpful example of how forensic science can become a far more sustainable field without sacrificing its scientific integrity is found in green chemistry. Sample preparation, solvent selection, miniaturisation, lower energy needs, and non-destructive analysis are the most important opportunities. Laboratories can objectively compare analytical techniques using analytical practice metrics such as the Analytical Eco-Scale, GAPI, ComplexGAPI, and AGREE. Therefore, methods that maximise analytical information while minimising sample usage, waste, energy consumption, and environmental risks should be the focus of forensic science's future. Cooperation between forensic scientists, analytical chemists, equipment manufacturers, regulatory bodies, and green chemistry researchers will be necessary to accomplish this goal. The final aim, then, must be the creation of forensic laboratories that are both scientifically reliable and environmentally sustainable.

References

1. Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*. Oxford University Press, New York, 1998.
2. Anastas, P. T.; Eghbali, N. Green Chemistry: Principles and Case Studies. *Chemical Society Reviews* **2010**, *39*, 301–312. https://doi.org/10.1039/B918763B.
3. Galuszka, A.; Migaszewski, Z. M.; Konieczka, P.; Namieśnik, J. Analytical Eco-Scale for Assessing the Greenness of Analytical Procedures. *TrAC Trends in Analytical Chemistry* **2012**, *37*, 61–72. https://doi.org/10.1016/j.trac.2012.03.013.
4. Galuszka, A.; Migaszewski, Z.; Namieśnik, J. The 12 Principles of Green Analytical Chemistry and the SIGNIFICANCE Mnemonic of Green Analytical Practices. *TrAC Trends in Analytical Chemistry* **2013**, *50*, 78–84. https://doi.org/10.1016/j.trac.2013.04.010.
5. Płotka-Wasylka, J. A New Tool for the Evaluation of the Analytical Procedure: Green Analytical Procedure Index. *Talanta* **2018**, *181*, 204–209. https://doi.org/10.1016/j.talanta.2018.01.013.
6. Płotka-Wasylka, J.; Wojnowski, W. Complementary Green Analytical Procedure Index (ComplexGAPI) and Software. *Green Chemistry* **2021**, *23*, 8657–8665. https://doi.org/10.1039/D1GC02318G.
7. Pena-Pereira, F.; Wojnowski, W.; Tobiszewski, M. AGREE—Analytical GREEnness Metric Approach. *Analytical Chemistry* **2020**, *92*, 10076–10082.
8. Armenta, S.; Garrigues, S.; de la Guardia, M. Green Analytical Chemistry. *TrAC Trends in Analytical Chemistry* **2008**, *27*, 497–511.
9. Tobiszewski, M.; Namieśnik, J. Green Analytical Chemistry—Theory and Practice. *Chemical Society Reviews* **2017**, *46*, 7313–7333.
10. Birk, A. et al. Green Chemistry: Developments and Perspectives for Sample Treatment in Forensic Methodologies. *WIREs Forensic Science* **2023**. https://doi.org/10.1002/wfs2.1497.
11. Brettell, T. A. Green Approaches in Forensic Separations—An Overview. *Separations* **2026**, *13*, 84.
12. de la Guardia, M.; Garrigues, S., Eds. *Challenges in Green Analytical Chemistry*. Royal Society of Chemistry, Cambridge, 2011.
13. Płotka-Wasylka, J.; Rutkowska, M.; Owczarek, K.; Tobiszewski, M.; Namieśnik, J. Extraction with Deep Eutectic Solvents. *TrAC Trends in Analytical Chemistry* **2017**, *88*, 80–90.
14. Koel, M. Ionic Liquids in Chemical Analysis. *Critical Reviews in Analytical Chemistry* **2005**, *35*, 177–192.