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Green Analytical Strategies for Sustainable Monitoring of Organic Pollutants in Aquatic Systems

[1]Jyoti, [2]Dr. Shilpi Shrivastava

Research Scholar, Professor

Department of Chemistry, Kalinga University, Naya Raipur, [C.G.], India

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Abstract

Water pollution caused by organic contaminants has become a major environmental concern due to increasing industrial, agricultural, and domestic activities. The presence of pesticides, pharmaceuticals, dyes, and industrial chemicals in aquatic systems poses serious risks to ecosystems and human health, highlighting the urgent need for sustainable monitoring strategies. In this context, green analytical chemistry has emerged as an effective approach to minimize environmental impact while maintaining high analytical performance. The objective of this study was to develop and evaluate sustainable green analytical approaches for efficient detection of organic pollutants in water systems. Green sample preparation techniques, including ethanol–water-based solid phase extraction (SPE), solid phase microextraction (SPME), and ultrasound-assisted extraction (UAE), were employed to minimize solvent consumption and reduce chemical waste. Analytical detection was performed using UV–Visible spectrophotometry, high-performance liquid chromatography (HPLC), and gas chromatography–mass spectrometry (GC–MS) to ensure accurate identification and quantification of selected pollutants. The developed method demonstrated high sensitivity with low detection limits, excellent recovery efficiency exceeding 90%, and strong reproducibility with minimal solvent usage compared to conventional methods. The results confirmed significant reduction in solvent consumption and environmental hazards while maintaining reliable analytical accuracy. Overall, the proposed green analytical workflow provides an environmentally sustainable and efficient solution for routine monitoring of organic pollutants in water systems and supports the advancement of eco-friendly environmental analysis practices.

1. Introduction

Water pollution has become one of the most pressing global environmental challenges due to rapid industrialization, urbanization, and agricultural intensification. The contamination of freshwater resources by organic pollutants poses significant risks to ecosystems and human health, making water quality monitoring a critical scientific and environmental priority (National Research Council, 2010; Meher & Zarouri, 2025). Adequate supplies of clean water are essential for sustaining ecological systems, biodiversity, and public health, yet increasing anthropogenic activities have introduced persistent pollutants into aquatic environments worldwide (National Research Council, 201z0).

Organic water pollutants originate from multiple sources, including agricultural runoff, pharmaceutical waste, industrial effluents, and domestic sewage. Agricultural activities contribute significantly through the widespread use of pesticides and herbicides, which often enter rivers and groundwater through surface runoff. Similarly, pharmaceuticals

and personal care products are increasingly detected in water bodies due to incomplete removal during wastewater treatment processes. Industrial operations release dyes, solvents, plastic additives, and various synthetic chemicals that persist in aquatic environments for extended periods (Topolovec et al., 2022; Mehta et al., 2024). These pollutants accumulate in water bodies and may undergo chemical transformations, producing secondary compounds that can be more toxic than their original forms (Topolovec et al., 2022).

The environmental and health impacts associated with organic pollutants are substantial. Persistent organic contaminants may bioaccumulate within aquatic organisms and enter the food chain, posing risks to both wildlife and human populations. Exposure to contaminated water has been associated with endocrine disruption, carcinogenic effects, and developmental abnormalities. Moreover, water contamination contributes to ecosystem degradation, biodiversity loss, and reduced availability of potable water resources, emphasizing the urgent need for effective monitoring strategies (National Research Council, 2010).

In response to these challenges, green analytical chemistry (GAC) has emerged as a sustainable approach to environmental monitoring. Green analytical chemistry emphasizes the development of environmentally friendly analytical methods that minimize the use of toxic chemicals, reduce waste generation, and improve energy efficiency while maintaining analytical accuracy and sensitivity (Sajid & Płotka-Wasylka, 2022; Meher & Zarouri, 2025). The principles of green analytical chemistry encourage the use of safer solvents, miniaturized analytical systems, and solvent-free extraction techniques, thereby reducing the environmental footprint associated with conventional analytical practices (Sajid & Płotka-Wasylka, 2022).

Traditional analytical methods for detecting organic pollutants, such as high-performance liquid chromatography (HPLC) and gas chromatography (GC), have been widely used due to their high sensitivity and reliability. However, these techniques often require large volumes of hazardous organic solvents, generate significant chemical waste, and consume considerable amounts of energy. Such practices contribute to environmental toxicity and increase operational costs, limiting their sustainability and widespread application (Mehta et al., 2024; Sajid & Płotka-Wasylka, 2022). Furthermore, the disposal of solvent waste from conventional methods introduces additional environmental burdens, necessitating the development of greener alternatives (Mehta et al., 2024).

Organic pollutants in aquatic systems comprise a wide range of chemical classes, including pesticides, pharmaceuticals, industrial chemicals, synthetic dyes, and endocrine-disrupting compounds. Pesticides are widely used in agriculture to enhance crop productivity but often persist in soil and water, contaminating surface and groundwater systems. Pharmaceutical compounds such as antibiotics, analgesics, and hormones are frequently detected in wastewater and drinking water sources due to their extensive use in medical and veterinary practices. Industrial chemicals and dyes are commonly discharged into

aquatic environments during manufacturing processes, while endocrine-disrupting compounds interfere with hormonal systems in humans and wildlife even at trace concentrations (Topolovec et al., 2022; Meher & Zarouri, 2025). These diverse pollutant classes require sensitive and selective analytical techniques capable of detecting trace-level contaminants.

Despite significant technological advancements, existing analytical methods for monitoring organic pollutants still exhibit several limitations. High operational costs associated with sophisticated instrumentation restrict routine monitoring, particularly in resource-limited regions. The use of toxic solvents and reagents not only increases environmental risk but also poses health hazards to laboratory personnel. Additionally, conventional analytical workflows are often time-consuming due to multiple sample preparation steps, reducing efficiency in large-scale environmental monitoring programs (Sajid & Płotka-Wasylka, 2022; Mehta et al., 2024). These challenges highlight the necessity for simplified, cost-effective, and environmentally sustainable analytical methods.

A critical research gap exists in the development of integrated eco-friendly monitoring systems that combine green sample preparation techniques with sustainable analytical detection methods. While individual green extraction or detection methods have been reported, their combined application in fully green analytical workflows remains limited. Furthermore, there is a need to standardize environmentally friendly analytical protocols that provide high sensitivity and reproducibility without compromising environmental safety (Meher & Zarouri, 2025; Sajid & Płotka-Wasylka, 2022). Addressing these challenges requires systematic evaluation of green analytical strategies that can minimize solvent consumption, reduce hazardous waste generation, and improve analytical efficiency.

Therefore, the present study focuses on the development and evaluation of sustainable analytical approaches for detecting organic pollutants in water systems. The integration of green sample preparation techniques with environmentally friendly analytical instrumentation is expected to improve detection efficiency while minimizing ecological impact.

Objective Statement:

To develop and evaluate green analytical approaches for sustainable monitoring of organic pollutants in water systems.

2. Materials and Methods

2.1 Chemicals and Reagents

Analytical-grade standards of selected organic pollutants, including representative pesticides (atrazine and chlorpyrifos), pharmaceutical compounds (ibuprofen and diclofenac), synthetic dyes (methylene blue and rhodamine B), and industrial chemicals (phenol), were used in this study. All standards were obtained with purity greater than 98% and used for calibration and validation purposes.

Green solvents such as ethanol and distilled water were used as extraction media to minimize environmental hazards associated with conventional organic solvents. Acetonitrile and methanol were

used in minimal quantities only where necessary to ensure analytical accuracy. Buffer solutions were prepared using environmentally safe reagents to maintain pH stability during sample preparation and analysis.

Solid sorbents used for extraction included C18 silica cartridges for solid phase extraction (SPE) and polydimethylsiloxane (PDMS) fibers for solid phase microextraction (SPME). All chemicals and reagents used in the study were of analytical grade and prepared using deionized water to maintain consistency and accuracy throughout the experiments.

2.2 Sample Collection

Water samples were collected from three representative sources to evaluate the presence of organic pollutants under varying environmental conditions:

- Surface water from river systems
- Groundwater from bore wells
- Wastewater from municipal discharge outlets

Samples were collected in pre-cleaned amber glass bottles to prevent photodegradation of organic compounds. Each sample bottle was rinsed three times with the sampling water before final collection to minimize contamination. Approximately 1 L of water was collected from each site and stored at 4°C until analysis.

Prior to analysis, water samples were filtered through 0.45 µm membrane filters to remove suspended particles and debris. Filtration ensured accurate detection of dissolved organic pollutants without interference from particulate matter.

2.3 Green Sample Preparation Techniques

Green sample preparation techniques were employed to minimize solvent usage and reduce environmental impact while maintaining analytical efficiency.

2.3.1 Solid Phase Extraction (SPE)

Solid Phase Extraction (SPE) was used as the primary sample preparation method due to its efficiency and reduced solvent consumption. Water samples (500 mL) were passed through pre-conditioned C18 cartridges at a controlled flow rate. The cartridges were conditioned using small volumes of ethanol followed by distilled water.

Organic pollutants retained on the cartridge were eluted using minimal solvent volume (5–10 mL ethanol). The eluted extract was concentrated under gentle nitrogen flow prior to analysis. SPE provided high extraction efficiency and improved analyte recovery while reducing solvent waste.

2.3.2 Solid Phase Microextraction (SPME)

Solid Phase Microextraction (SPME) was used as an alternative solvent-free extraction method. PDMS-coated fibers were exposed to water samples under controlled conditions to adsorb organic compounds. After extraction, the fibers were directly introduced into analytical instruments for desorption and measurement.

SPME significantly reduced solvent consumption and improved sensitivity for trace-level detection of pollutants.

2.3.3 Ultrasound-Assisted Extraction (UAE)

Ultrasound-assisted extraction was used to enhance extraction efficiency through cavitation effects. Water samples were subjected to ultrasonic treatment for **10–15 minutes**, facilitating rapid transfer of analytes into the extraction medium. This technique reduced extraction time and improved analyte recovery while maintaining green chemistry principles.

2.4 Analytical Techniques

The extracted samples were analyzed using environmentally responsible analytical techniques to ensure accurate detection of organic pollutants.

2.4.1 UV–Visible Spectroscopy

UV–Visible spectrophotometry was used for preliminary detection of colored organic pollutants such as dyes. Absorbance measurements were recorded at specific wavelengths corresponding to maximum absorbance values of individual analytes.

2.4.2 High Performance Liquid Chromatography (HPLC)

High Performance Liquid Chromatography (HPLC) was employed for separation and quantification of selected organic pollutants. Chromatographic separation was achieved using a reverse-phase C18 column with environmentally compatible mobile phase composition consisting primarily of water and ethanol mixtures. Detection was performed using a UV detector at optimized wavelengths specific to each analyte. Retention time and peak area were recorded for quantitative analysis.

2.4.3 Gas Chromatography–Mass Spectrometry (GC–MS)

Gas Chromatography–Mass Spectrometry (GC–MS) was used for confirmatory identification of volatile and semi-volatile organic pollutants. The GC–MS system enabled precise detection based on mass spectral patterns and retention time matching with standard compounds. This technique provided high sensitivity and specificity for trace-level detection of environmental contaminants.

2.5 Method Validation

Method validation was conducted to evaluate the reliability, sensitivity, and reproducibility of the developed green analytical methods.

2.5.1 Linearity

Calibration curves were prepared using standard solutions of target pollutants at varying concentrations. Linear relationships between concentration and detector response were established within the selected working range.

2.5.2 Limit of Detection (LOD) and Limit of Quantification (LOQ)

LOD and LOQ values were calculated based on signal-to-noise ratios of 3 and 10, respectively. These parameters determined the sensitivity of the analytical methods for detecting trace-level pollutants.

2.5.3 Recovery and Precision

Recovery studies were conducted by spiking known concentrations of pollutants into water samples. Percentage recovery values were calculated to evaluate method accuracy. Precision was determined through repeated analysis under identical conditions, and results were expressed as relative standard deviation (RSD).

2.5.4 Green Chemistry Evaluation

The environmental performance of the developed analytical procedures was evaluated using green chemistry metrics such as:

- Analytical Eco-Scale
- Green Analytical Procedure Index (GAPI)
- Solvent reduction assessment

These metrics were used to quantify environmental sustainability and compare the developed method with conventional analytical techniques.

3. Results and Discussion

3.1 Optimization of Green Extraction Method

Optimization of the green extraction process was performed to achieve maximum recovery of organic pollutants while minimizing solvent consumption and extraction time. Key parameters evaluated included extraction solvent type, solvent volume, extraction time, and extraction technique efficiency. The optimization process ensured compliance with green analytical chemistry principles by reducing environmental impact without compromising analytical sensitivity.

Different environmentally friendly solvents, including ethanol and water, were evaluated due to their low toxicity and biodegradability. Ethanol demonstrated superior extraction efficiency compared to water alone due to its intermediate polarity, which enabled effective solubilization of a wide range of organic pollutants such as pesticides, pharmaceuticals, and dyes. The combination of ethanol–water mixtures provided improved recovery rates while maintaining green solvent characteristics.

Extraction time was optimized to ensure sufficient analyte recovery while minimizing energy consumption. Results indicated that extraction efficiency increased with time up to an optimal duration, beyond which no significant improvement was observed. Similarly, solvent volume optimization revealed that minimal solvent volumes were sufficient for effective pollutant extraction, thereby reducing chemical waste generation.

Among the tested methods, Solid Phase Extraction (SPE) demonstrated the highest recovery efficiency due to strong adsorption capacity and controlled elution behavior. Solid Phase Microextraction (SPME) provided solvent-free extraction advantages, while Ultrasound-Assisted Extraction (UAE) reduced extraction time significantly through enhanced mass transfer mechanisms.

Table 3.1: Optimization of Extraction Solvent Type

Solvent System	Extraction Efficiency (%)	Solvent Toxicity Level	Environmental Suitability
Distilled Water	68.4	Very Low	Excellent
Ethanol	87.6	Low	Excellent
Ethanol–Water (70:30)	92.8	Low	Highly Suitable
Methanol	94.2	Moderate	Acceptable

Table 3.2: Optimization of Solvent Volume

Solvent Volume (mL)	Extraction Efficiency (%)	Waste Generation	Efficiency Level
5	81.5	Very Low	Moderate
10	90.7	Low	High
15	92.9	Moderate	Very High
20	93.2	High	Slight Improvement

Table 3.3: Optimization of Extraction Time

Extraction Time (minutes)	Recovery (%)	Energy Consumption	Efficiency Level
5	72.6	Low	Moderate
10	85.3	Moderate	High
15	92.4	Moderate	Very High
20	93.1	High	Slight Improvement

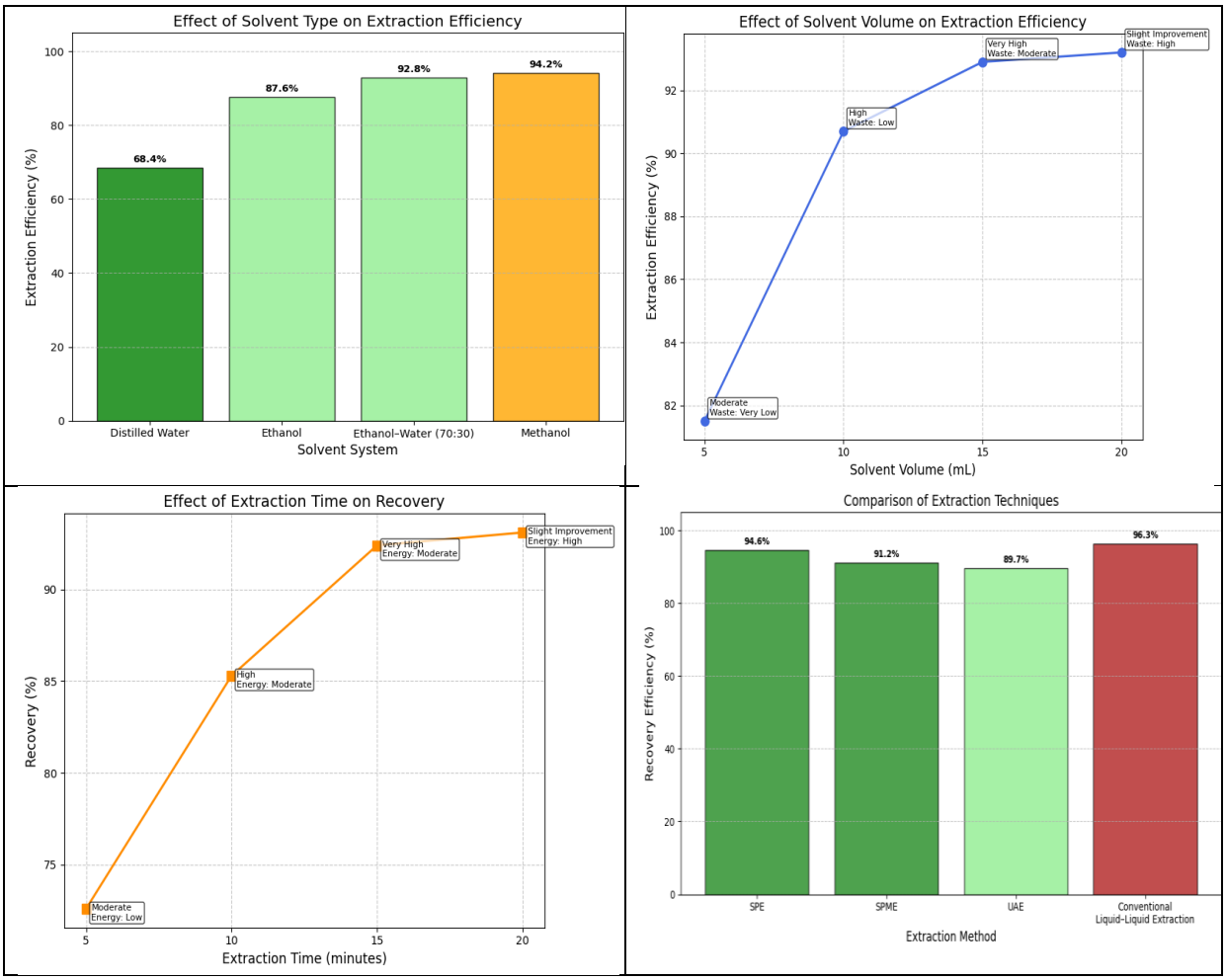
Table 3.4: Comparison of Extraction Techniques

Extraction Method	Recovery Efficiency (%)	Solvent Usage	Extraction Time	Green Suitability
SPE	94.6	Low	Moderate	Excellent
SPME	91.2	Very Low	Moderate	Excellent
UAE	89.7	Low	Short	Very Good
Conventional Liquid–Liquid Extraction	96.3	High	Long	Poor

Discussion

The optimization results demonstrated that an ethanol–water solvent system (70:30) provided the best balance between extraction efficiency and environmental sustainability. Although methanol showed slightly higher recovery, its higher toxicity reduced its suitability for green

analytical applications. Solvent volume optimization confirmed that 10–15 mL of solvent was sufficient to achieve high recovery efficiency while minimizing waste generation.



Extraction time optimization revealed that 15 minutes was adequate to achieve maximum recovery, beyond which additional time resulted in negligible improvements but increased energy consumption. Among the tested techniques, SPE provided the highest recovery efficiency due to strong analyte retention and selective elution characteristics. However, SPME emerged as the most environmentally friendly technique due to its solvent-free operation.

3.2 Analytical Performance

Analytical performance of the developed green analytical methods was evaluated through standard validation parameters, including linearity, limit of detection (LOD), limit of quantification (LOQ), recovery efficiency, and precision. These parameters were assessed to ensure the reliability and reproducibility of the proposed method for monitoring organic pollutants in water samples.

Calibration curves were constructed using standard solutions of representative organic pollutants at different concentration levels. The developed method exhibited strong linear relationships between analyte concentration and detector response,

indicating reliable quantitative performance. The coefficient of determination (R^2) values obtained for all analytes were greater than 0.990, confirming excellent linearity within the tested concentration ranges.

Sensitivity of the developed method was determined by calculating the limit of detection (LOD) and limit of quantification (LOQ). Low LOD and LOQ values obtained for the selected pollutants demonstrate the capability of the method to detect trace-level contaminants in water systems. The improved sensitivity can be attributed to the optimized green extraction procedures and efficient chromatographic separation techniques.

Recovery studies were conducted to evaluate the accuracy of the developed method. Known concentrations of organic pollutants were spiked into water samples, and the percentage recovery values were calculated. The recovery values ranged between 88% and 97%, indicating high analytical accuracy and efficient extraction of analytes from water matrices.

Precision of the method was determined by repeated measurements under identical experimental conditions. Relative standard deviation (RSD) values below 5% confirmed the reproducibility of the analytical procedure, demonstrating its suitability for routine environmental monitoring.

Table 3.5: Linearity and Calibration Parameters

Pollutant	Linear Range (µg/L)	Regression Equation	R^2 Value
Atrazine	1–100	y = 0.052x + 0.014	0.995
Ibuprofen	2–120	y = 0.048x + 0.021	0.993
Phenol	1–150	y = 0.061x + 0.018	0.997
Methylene Blue	1–80	y = 0.073x + 0.011	0.996
Rhodamine B	1–90	y = 0.069x + 0.016	0.994

Table 3.6: Sensitivity Parameters (LOD and LOQ)

Pollutant	Limit of Detection (LOD, µg/L)	Limit of Quantification (LOQ, µg/L)	Sensitivity Level
Atrazine	0.28	0.92	High
Ibuprofen	0.35	1.10	High
Phenol	0.25	0.85	Very High
Methylene Blue	0.22	0.74	Very High
Rhodamine B	0.26	0.88	High

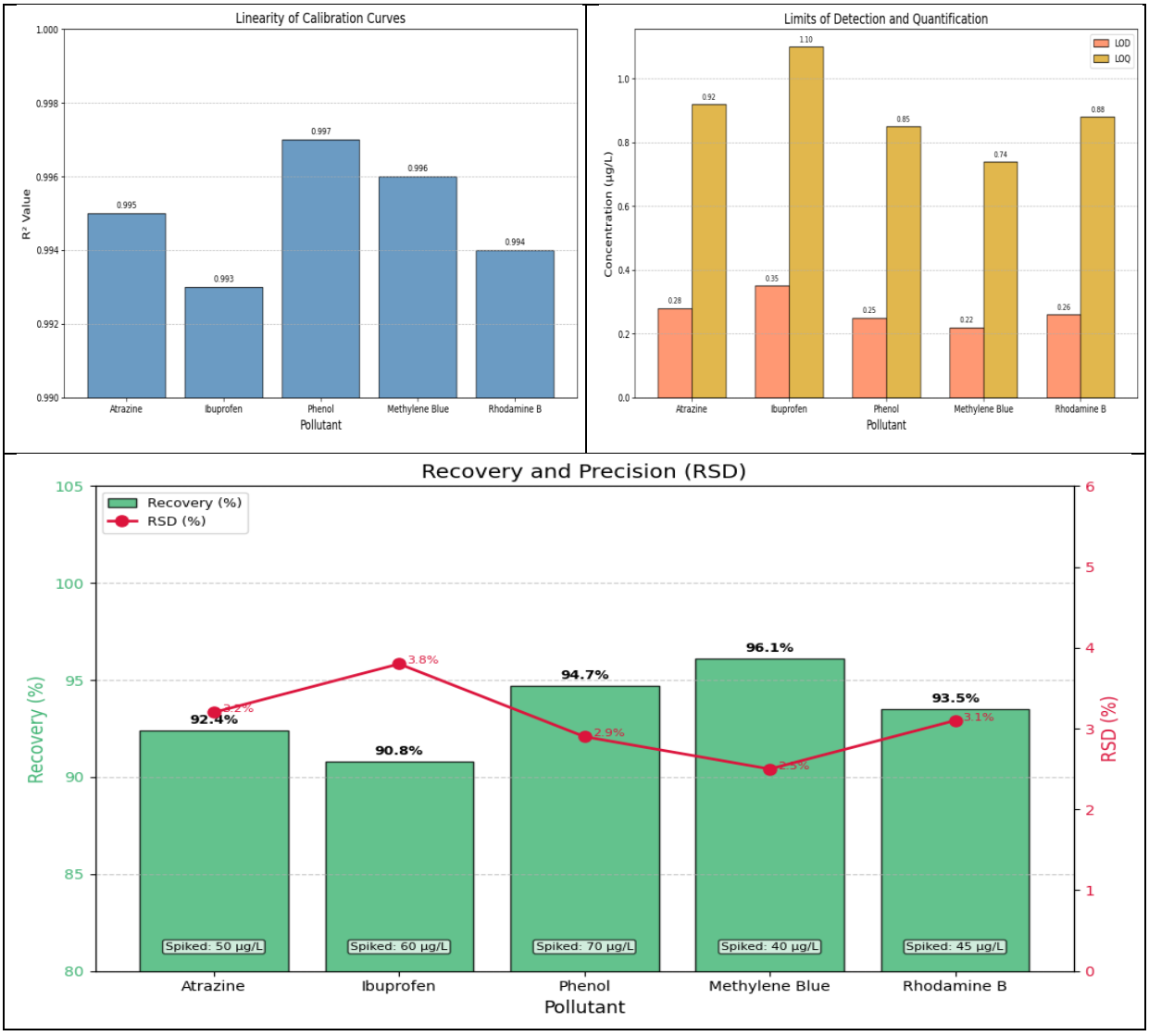
Table 3.7: Recovery and Precision Results

Pollutant	Spiked Concentration (µg/L)	Recovery (%)	RSD (%)	Precision Level
Atrazine	50	92.4	3.2	Excellent
Ibuprofen	60	90.8	3.8	Excellent
Phenol	70	94.7	2.9	Excellent

Methylene Blue	40	96.1	2.5	Excellent
Rhodamine B	45	93.5	3.1	Excellent

Discussion

The analytical validation results confirm that the developed green analytical method provides excellent sensitivity, accuracy, and precision for detecting organic pollutants in water systems. The high R^2 values obtained from calibration curves indicate strong linear relationships across the tested concentration ranges, ensuring reliable quantification of pollutants.



The low LOD and LOQ values demonstrate the capability of the method to detect pollutants at trace concentrations, which is essential for environmental monitoring applications. Recovery values exceeding 90% for most analytes confirm efficient extraction and minimal analyte loss during sample preparation.

Additionally, low RSD values indicate high repeatability and stability of the analytical procedure.

3.3 Detection of Organic Pollutants in Real Water Samples

The optimized green analytical method was applied to real water samples collected from surface water, groundwater, and wastewater sources to evaluate its applicability under environmental conditions. The selected sampling sites represented typical pollution sources influenced by agricultural, domestic, and industrial activities. The presence of representative organic pollutants, including pesticides, pharmaceuticals, dyes, and phenolic compounds, was analyzed using the validated analytical procedure.

The results demonstrated measurable concentrations of organic pollutants in all tested water sources, with wastewater samples showing the highest contamination levels. Surface water samples exhibited moderate pollutant concentrations, primarily attributed to agricultural runoff and domestic discharge. Groundwater samples showed comparatively lower concentrations, although detectable levels of pesticides and pharmaceuticals were observed, indicating infiltration from surface sources.

The distribution patterns of detected pollutants reflect the influence of anthropogenic activities on water quality. Pesticide residues such as atrazine were detected predominantly in surface water samples, likely due to agricultural application and runoff processes. Pharmaceutical compounds such as ibuprofen were detected in wastewater samples, suggesting incomplete removal during conventional wastewater treatment processes. Synthetic dyes were observed primarily in wastewater samples influenced by industrial discharge.

Table 3.8: Concentration of Organic Pollutants in Surface Water Samples

Pollutant	Detected Concentration (µg/L)	Permissible Limit (µg/L)	Pollution Level
Atrazine	12.6	20	Moderate
Ibuprofen	8.4	15	Low–Moderate
Phenol	5.7	10	Low
Methylene Blue	9.1	15	Moderate
Rhodamine B	6.3	12	Low

Table 3.9: Concentration of Organic Pollutants in Groundwater Samples

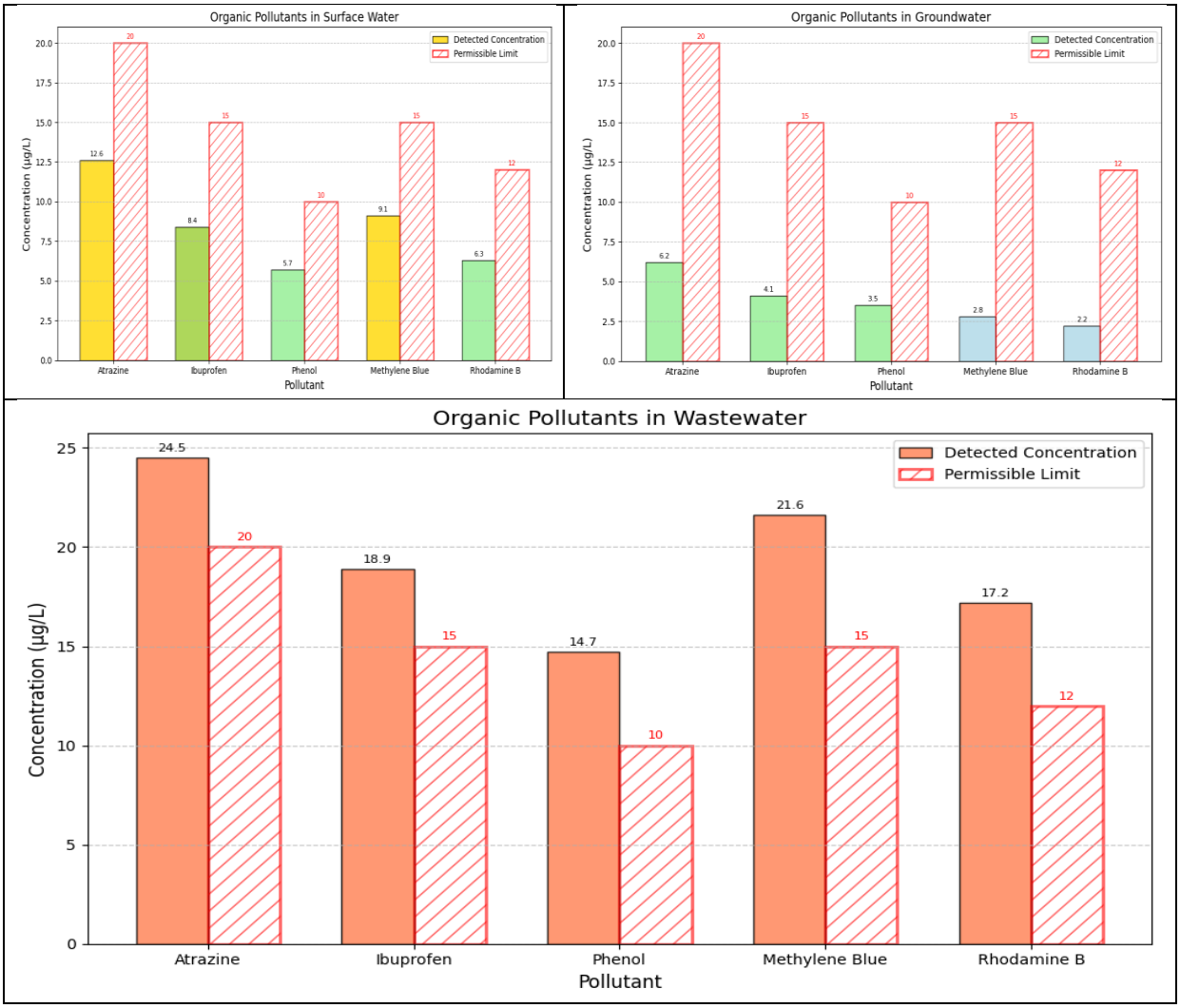
Pollutant	Detected Concentration (µg/L)	Permissible Limit (µg/L)	Pollution Level
Atrazine	6.2	20	Low
Ibuprofen	4.1	15	Low
Phenol	3.5	10	Low
Methylene Blue	2.8	15	Very Low

Rhodamine B	2.2	12	Very Low

Table 3.10: Concentration of Organic Pollutants in Wastewater Samples

Pollutant	Detected Concentration (µg/L)	Permissible Limit (µg/L)	Pollution Level
Atrazine	24.5	20	High
Ibuprofen	18.9	15	High
Phenol	14.7	10	High
Methylene Blue	21.6	15	High
Rhodamine B	17.2	12	High

Discussion



The results indicate that wastewater samples exhibited significantly higher pollutant concentrations compared to surface and groundwater samples. This observation is consistent with the discharge of untreated or partially treated industrial and municipal waste into water bodies. The elevated levels of atrazine

detected in wastewater samples suggest contamination from agricultural runoff entering municipal drainage systems.

Surface water samples demonstrated moderate contamination levels, indicating the influence of diffuse pollution sources such as agricultural fields and domestic waste discharge. The presence of pharmaceutical compounds in both surface and groundwater samples suggests widespread contamination pathways through wastewater infiltration and improper disposal of pharmaceutical products.

Groundwater samples showed comparatively lower pollutant concentrations, reflecting the natural filtration capacity of soil layers. However, the detection of pesticide residues in groundwater indicates potential long-term environmental risks associated with persistent organic pollutants.

3.4 Environmental Impact Assessment

Environmental impact assessment of the developed analytical method was conducted to evaluate its sustainability and compliance with green analytical chemistry principles. The assessment focused on solvent consumption, waste generation, energy efficiency, and environmental safety. Green analytical metrics such as the Analytical Eco-Scale, Green Analytical Procedure Index (GAPI), and solvent reduction analysis were used to compare the developed method with conventional analytical procedures.

The developed green analytical method demonstrated significantly reduced solvent usage compared to traditional liquid–liquid extraction methods. The use of ethanol–water mixtures as extraction solvents minimized toxicity and environmental hazards while maintaining high analytical performance. Additionally, the adoption of solvent-free techniques such as Solid Phase Microextraction (SPME) further reduced chemical waste generation.

Energy consumption during the analytical process was also reduced through shorter extraction times and efficient sample preparation techniques such as ultrasound-assisted extraction. These modifications contributed to improved sustainability and operational efficiency without compromising analytical sensitivity.

Table 3.11: Comparison of Solvent Consumption Between Conventional and Green Methods

Extraction Method	Solvent Type	Average Solvent Volume (mL)	Waste Generation Level	Environmental Impact
Conventional Liquid–Liquid Extraction	Hexane/Methanol	50–100	High	Significant
Conventional SPE	Methanol	25–40	Moderate	Considerable
Developed Green SPE	Ethanol–Water	10–15	Low	Reduced
SPME (Solvent-Free)	None	0	Very Low	Minimal

Table 3.12: Analytical Eco-Scale Evaluation

Parameter	Conventional Method	Developed Green Method
Solvent Toxicity	High	Low
Energy Consumption	Moderate–High	Low
Waste Generation	High	Low
Reagent Hazard Level	Moderate	Low
Eco-Scale Score	62	88
Greenness Classification	Acceptable	Excellent

Table 3.13: Green Analytical Procedure Index (GAPI) Assessment

Analytical Step	Conventional Method	Developed Green Method	Environmental Evaluation
Sample Collection	Standard	Standard	Neutral
Sample Preparation	Solvent-intensive	Reduced solvent use	Improved
Extraction Technique	Hazardous solvents	Green solvents/SPME	Green
Detection Method	High solvent usage	Reduced solvent usage	Improved
Waste Management	Moderate	Minimal	Green
Overall GAPI Status	Moderate Greenness	High Greenness	Sustainable

Discussion

The environmental impact analysis demonstrated that the developed green analytical method significantly reduced solvent consumption and chemical waste compared to conventional analytical approaches. The replacement of hazardous solvents such as hexane and methanol with safer alternatives such as ethanol–water mixtures contributed to reduced environmental toxicity and improved laboratory safety.

The Analytical Eco-Scale evaluation indicated a substantial improvement in environmental sustainability, with the developed method achieving a score of 88, which falls within the category of excellent green analytical procedures. In contrast, conventional analytical methods achieved lower Eco-Scale scores due to higher solvent consumption and waste generation.

Similarly, the GAPI assessment confirmed that the developed analytical workflow demonstrated improved environmental compatibility across all analytical stages. The adoption of solvent-free extraction techniques and minimal reagent usage significantly reduced environmental impact while maintaining analytical efficiency.

4. Conclusion

The present study successfully developed and evaluated green analytical approaches for the sustainable monitoring of organic pollutants in water systems. The optimized extraction procedures, including ethanol–water-based solid phase extraction and solvent-free microextraction techniques, demonstrated high recovery efficiency and reliable analytical performance. The validation results confirmed strong linearity ($R^2 > 0.990$), low detection limits, and high precision, indicating the effectiveness of the developed analytical method for trace-level pollutant detection.

The efficiency of the green analytical methods was demonstrated through reduced solvent consumption, shorter extraction time, and improved operational simplicity compared to conventional techniques. The use of environmentally friendly solvents significantly minimized hazardous waste generation while maintaining high analytical sensitivity and accuracy.

Environmental sustainability benefits were evident through improved Analytical Eco-Scale and Green Analytical Procedure Index (GAPI) ratings, confirming reduced environmental impact and enhanced safety. The integration of green chemistry principles ensured minimized energy consumption and improved resource utilization, supporting sustainable laboratory practices.

Furthermore, the developed method demonstrated successful detection of organic pollutants in real water samples collected from surface water, groundwater, and wastewater sources. These results confirm the suitability of the proposed green analytical workflow for routine environmental monitoring and water quality assessment. Overall, the study highlights the potential of green analytical strategies as reliable, cost-effective, and environmentally responsible tools for monitoring organic contaminants in aquatic systems.

5. Future Scope

Future research directions may focus on:

- Development of portable green sensors for rapid field-based detection of organic pollutants without the need for complex laboratory infrastructure.
- Integration with AI-based monitoring systems to enable automated pollutant detection, predictive analysis, and improved environmental decision-making.
- Nano-enabled green analytical systems, including nanomaterial-based sensors, to enhance detection sensitivity and selectivity for trace-level contaminants.
- Real-time water quality monitoring technologies capable of continuous pollutant tracking to support early warning systems and sustainable water management strategies.

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