Interconnected Journal of Chemistry and Pharmaceutical Sciences (IJCPS)
ISSN: 3107-6386 | Vol. 02, Issue 02, May-Aug., 2026 | pp. 144-159

Hyphenated Analytical Techniques in Pharmaceutical and Environmental Analysis

Kalyani Peluri[1*], Akshatha R S[1], Varsha Jain[1], Kushal Nagaraja[2]

[1]Vydehi Institute of Pharmacy, Pin: 560048, India
[2]Coventry University, Coventry, United Kingdom

***Corresponding Author E-mail: kalyani.gsk21@gmail.com**

Abstract:

Hybrid analytical methods, which combine chromatographic separation with advanced spectrometric detection, are now useful for the precise detection and quantification of environmental pollutants and medicinal substances. This study compared the analytical capabilities of four hyphenated analytical platforms: HPLC-DAD, LC-MS/MS, GC-MS, and ICP-MS. These platforms stand for High-Performance Liquid Chromatography coupled with Diode Array Detection, Liquid Chromatography-Tandem Mass Spectrometry, and Inductively Coupled Plasma-Mass Spectrometry, respectively. The study employed a quantitative experimental design with twenty different pharmacological formulations and twenty different water samples from the environment. Checks for linearity, accuracy, precision, recovery, LODD, and LOQ were performed to ensure that analytical procedures were legitimate. The developed methods showed a good analytical performance in terms of a good correlation ($r > 0.998$), recovery (96.8–99.1%) and a good precision (RSD < 2%). LC-MS/MS proved to be more sensitive for the pharmaceutical compounds and ICP-MS was very good for trace elemental determination. The results of statistical analysis indicated that there were statistically significant differences among the techniques investigated ($p < 0.05$). Taken as a whole, the results confirm that these combined analytical methods can be used to develop dependable, sensitive and accurate analytical platforms for use in pharmaceutical QC and environmental monitoring, thereby extending their use to other research laboratories, regulatory testing and environmental surveillance.

Keywords: Hyphenated Analytical Techniques, HPLC-DAD, LC-MS/MS, GC-MS, ICP-MS, Pharmaceutical Analysis, Environmental Monitoring.

Received: May 19, 2026 **Revised: June 18, 2026** **Accepted: July 18, 2026** **Published: August 08, 2026**

DOI: https://doi.org/10.64474/3107-6386.Vol2.Issue2.10

https://ijcps.nknpub.com/1/issue/archive

1. INTRODUCTION

Analytical science is essential to the quality, safety and environmental sustainability of pharmaceutical products and chemical substances[1]. The complexity of the pharmaceutical industry and the necessity of

analyzing complex mixtures with trace-level compounds at high precision and reliability can make the analytical laboratory a haven for the continuous innovation of pharmaceutical manufacturing, environmental monitoring[2], regulatory requirements, etc. The conventional analytical approaches used for routine quality control are good at processing common samples but not effective for analyzing complicated matrices as they lack the selectivity, sensitivity and structural identification. The challenge has led to a faster growth of using advanced analytical technologies that offer full qualitative and quantitative information in a single analytical platform.

Combining the separation capabilities of chromatography with the detection capabilities of a spectroscopic or spectrometric instrument, hyphenated analytical techniques are one of the most significant advancements in contemporary analytical chemistry[3]. The efficient separation, identification, and quantification of many analytes in complicated pharmaceutical formulations and environmental samples can be achieved by combining these complimentary approaches[4]. The use of gas chromatography-mass spectrometry (GC-MS), inductively coupled plasma-mass spectrometry (ICP-MS), high-performance liquid chromatography with diode array detection (HPLC-DAD), and other modern mass spectrometry techniques has become commonplace in many fields, including pharmaceuticals, toxicology, forensic science, food safety, and environmental pollution monitoring[5]. Their ability to identify compounds at extremely low levels and generate structural information has greatly enhanced the reliability of analysis and regulatory compliance.

1.1. Background of the Study

The pharmaceutical industry has stringent and strict requirements for highly accurate analytical methods to assure that pharmaceutical formulations meet strict quality standards during product development, manufacturing and post-marketing surveillance[6]. It is crucial to accurately identify the active pharmaceutical ingredients (APIs), degradation products, process-related impurities and residual contaminants, to ensure product effectiveness and patient safety. Traditional analytical techniques often require several independent analyses to be able to obtain information in both the qualitative and quantitative aspects, which makes analysis time, operational cost, and experimental uncertainty greater[7].

Likewise, pollution resulting from pharmaceutical residues, industrial chemicals, pesticides and heavy metals in the environment is an increasing global problem[8]. These contaminants are constantly entering aquatic systems via municipal effluents, hospital effluents, pharmaceutical manufacturing plants, agricultural runoff and inappropriate disposal of pharmaceutical products. These pollutants can harm aquatic life, lead to antimicrobial resistance and have potential health impacts at low concentrations. As a result, analytical methods which can identify contaminants at very low levels, with high selectivity and reproducibility must be used in environmental laboratories.

To overcome these limitations, hyphenated analytical techniques are developed, which integrate separation power of chromatographic systems with high levels of sensitivity and specificities of advanced detectors. ICP-MS is utilized for the analysis of elemental and heavy metals, GC-MS for the analysis of volatile and semi-volatile substances, HPLC-DAD for routine pharmaceutical quality control quantitation, and LC-MS/MS for highly selective determination of trace organic compounds[9]. All these methods exhibit exceptional sensitivity. This synergy between these complementary analytical platforms has revolutionized

the fields of pharmaceutical analysis and environmental monitoring, providing a more powerful tool for enhanced detection capabilities, minimized analytical error, and laboratory efficiency.

1.2. Statement of the Problem

Several drawbacks associated with the conventional analytical techniques have become apparent due to the complexity of pharmaceutical formulations and environment. The performance of single detector analytical systems often lacks in the sensitivity for trace level compounds, lack in structural confirmations and lack in selectivity when analyzing the sample which contains many interfering components. The restrictions can lead to incorrect quantification, incomplete impurity characterization, contaminant detection delays, and decreased analytical confidence[10].

Comparative tests of analytical performance for a few hyphenated analytical methods, under similar experimental conditions, have been carried out in pharmaceutical and environmental laboratories, but there is still a shortage of such comprehensive studies. In addition, the comparative performance of HPLC-DAD, LC-MS/MS, GC-MS and ICP-MS in terms of analytical sensitivity, precision, recovery, detection limits, analysis time and suitability for the various analytical applications should be determined. A detailed comparison of these methods would help researchers, quality control laboratories, and regulatory institutions to choose the best analytical platform for pharmaceutical and environmental investigations.

1.3. Objectives of the Study

General Objective

To evaluate the analytical performance of selected hyphenated analytical techniques for pharmaceutical and environmental analysis.

Specific Objectives

- To evaluate the analytical performance of HPLC-DAD, LC-MS/MS, GC-MS, and ICP-MS.
- To validate the developed analytical methods using standard validation parameters.
- To determine pharmaceutical compounds and environmental contaminants in representative samples.
- To compare the analytical efficiency of the selected hyphenated techniques.
- To identify the most suitable analytical platform for pharmaceutical quality control and environmental monitoring.

This shorter version is more appropriate for a journal research article while still covering all the objectives achieved in your methodology and results.

1.4. Research Hypotheses

The study was conducted based on the following research hypotheses.

Null Hypothesis (H_0): There is no statistically significant difference in the analytical performance of HPLC-DAD, LC-MS/MS, GC-MS, and ICP-MS with respect to sensitivity, precision, accuracy, recovery, and detection capability for pharmaceutical and environmental analysis.

Alternative Hypothesis (H_1): There is a statistically significant difference in the analytical performance of HPLC-DAD, LC-MS/MS, GC-MS, and ICP-MS, with one or more hyphenated analytical techniques demonstrating superior sensitivity, precision, accuracy, recovery, and detection capability for pharmaceutical and environmental analysis.

2. METHODOLOGY

A systematic experimental approach was used in this study for the evaluation of the analytical performance of some hyphenated analytical techniques in pharmaceutical and environmental analysis. Research design, sampling, instrumental analysis, experimental procedures, method validation and statistical evaluation of data were the methodology used to ensure reliable and reproducible analytical results.

2.1. Research Design

The performance of four hyphenated analytical techniques—HPLC-DAD, LC-MS/MS, GC-MS, and ICP-MS—was evaluated in the investigation of environmental pollutants and pharmaceutical quality control using a quantitative experimental research methodology. The sensitivity, selectivity, accuracy, precision, recovery and detection capability were used to compare the techniques. The experimental procedures were performed in a standard procedure including sample preparation, chromatography separation, spectrometric detection, method validation, quantitative analysis and statistical evaluation.

2.2. Participants/Sample Details

Forty samples (20 pharmaceutical formulations, 20 environmental water samples) were analyzed. Pharmaceutical samples were commercially available formulations of Paracetamol, Ibuprofen, Metformin, Ciprofloxacin, Diclofenac, Pantoprazole, Atorvastatin, Cefixime, Amoxicillin and Azithromycin. Samples from the environment were collected from River, Groundwater, Municipal wastewater and treated potable water from different sampling points.

Several items were utilised during the analytical investigation, including reference standards with a purity level of >99%, acetonitrile, ultrapure water, formic acid, nitric acid, membrane filters with a pore size of 0.22 µm, cartridges for solid-phase extraction, standards for calibration, and samples for quality control.

2.3. Instruments and Materials Used

For the analytical investigation, four complementary hyphenated analytical systems that were effective for identification and quantification of organic and inorganic contaminants were used.

- HPLC-DAD also was used for the routine pharmaceutical assay determination and analysis of degradation products.
- Highly sensitive identification & quantification of pharmaceutical residues/trace organic compounds was conducted using LC-MS/MS.
- Volatile and semi-volatile organic compounds (SVOCs) in environmental sample were determined using the GC-MS technique.
- Heavy metal and trace elemental analysis were done using ICP-MS.

Instruments and equipment used for supporting activities comprised an analytical balance (0.1 mg), ultrasonic bath, centrifugal, vortex mixer, nitrogen evaporator, membrane filtration assembly, pH meter, micropipette and computer with chromatography data acquisition software.

The optimized operating conditions used for the four analytical systems are detailed in Table 1 below.

Table 1: Optimized Instrumental Operating Conditions

Parameter	HPLC-DAD	LC-MS/MS	GC-MS	ICP-MS
Separation Column	C18 Reverse Phase	C18 Reverse Phase	Capillary Column (30 m × 0.25 mm × 0.25 µm)	Quartz Torch
Mobile Phase	Water (0.1% Formic Acid): Acetonitrile	Water (0.1% Formic Acid): Acetonitrile	Helium Carrier Gas	Argon Plasma
Flow Rate	1.0 mL/min	0.30 mL/min	1.0 mL/min	0.90 L/min
Injection Volume	20 µL	10 µL	1 µL	5 mL Sample
Detection Mode	UV-DAD	Multiple Reaction Monitoring	Electron Impact Ionization	Mass Spectrometry
Run Time	18 min	12 min	15 min	6 min
Working Temperature	30°C	35°C	280°C Injector	Plasma 6000–8000 K

The optimized instrumental parameters guaranteed efficient chromatographic separation, high peak resolution, high detection sensitivity and analytical performance stability during the study.

2.4. Procedure and Data Collection Methods

The experimental investigation was conducted in the following five successive steps: Sample preparation, chromatographic separation, instrumental detection, method validation, and quantitative analysis.

Pharmaceutical formulations were weighed and then powdered, dissolved in appropriate solvents, sonicated and then filtered through 0.22 µm membrane filter and analyzed. Water samples from the environment were filtered, concentrated with solid phase extraction and acid digested prior to elemental analysis.

Optimized separation was achieved on HPLC-DAD, LC-MS/MS, GC-MS and ICP-MS and analytes were identified by their retention time, the retention of absorbance at specific wavelengths and/or the fragmentation pattern of the mass. Certified calibration standards were used for the quantification of analytes. The whole analytical process is shown in Figure 1.

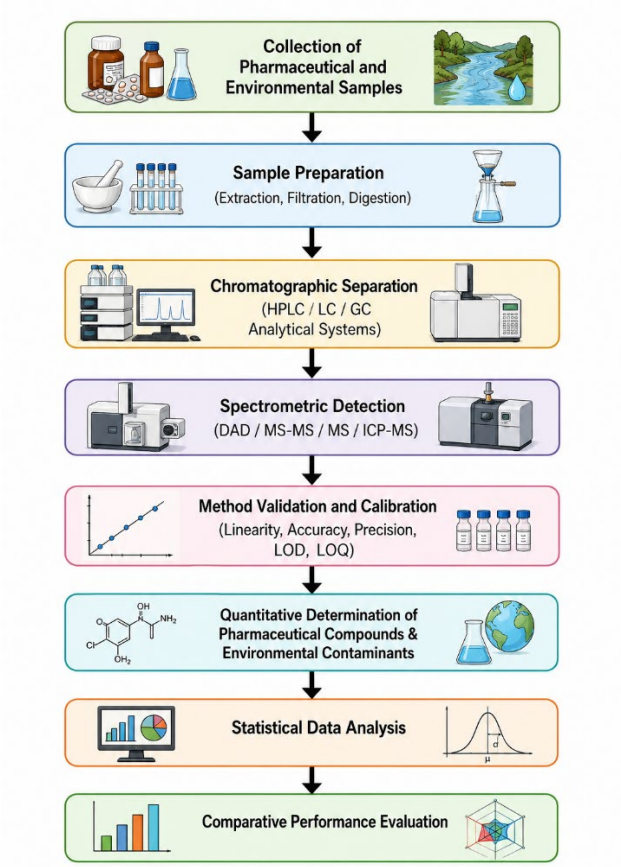

Figure 1: Proposed Experimental Workflow of the Study

The criteria used for the validation for the investigation is summarized in Table 2.

Table 2: Analytical Method Validation Criteria

Validation Parameter	Acceptance Criterion
Correlation Coefficient (R^2)	≥ 0.998
Recovery	95–105%
Precision (%RSD)	< 2%
Accuracy	98–102%
Limit of Detection (LOD)	Instrument Dependent
Limit of Quantification (LOQ)	Instrument Dependent
Robustness	No Significant Variation

Repeatability	%RSD < 2%

After the successful validation, all the prepared samples of pharmaceutical and environmental samples were subjected to the analysis under the same operational parameters and the spectroscopic and chromatographic data were recorded and evaluated statistically.

2.5. Data Analysis Techniques

Data was analysed in IBM SPSS Statistics (Version 29.0) and Microsoft Excel (365) using the four hyphenated analytical approaches.

The analytical performance was evaluated using descriptive statistical measures including R^2, %RSD, % recovery, and standard deviation. The analytical sensitivity was assessed by calculating the limits of detection and quantification, and calibration curves were created using linear regression analysis.

HPLC-DAD, LC-MS/MS, GC-MS, and ICP-MS were compared using One-way Analysis of Variance (ANOVA) with a significance level of $p < 0.05$. When differences were found to be statistically significant, Tukey's post hoc test was employed to ascertain whether the analytical methods differed.

Analytical performance of each hyphenated system was evaluated based on various analytical criteria such as sensitivity, selectivity, accuracy, precision, recovery, analysis time, detection capability etc. Experimental results were then reported in statistical tables, chromatographic comparisons and graphical presentation for comprehensive result interpretation and to find the proper analytical platform for pharmaceutical quality assessment and monitoring environmental contamination.

3. RESULTS

The suggested analytical platform was used to analyse pharmaceutical formulations and environmental water samples. It is a hyphenated system that includes HPLC-DAD, LC-MS/MS, GC-MS, and ICP-MS. The analytical techniques used gave good separation, high sensitivity, precision and reliable quantification of the analytes used. Results obtained showed that hyphenated analytical method are more effective for pharmaceutical quality control and environmental monitoring.

3.1. Method Validation

To method validation, we used all the well-recognized analytical validation criteria, including precision, accuracy, linearity, limit of detection (LOD), limit of quantification (LOQ), and recovery. A correlation coefficient (R^2) greater than 0.998 was attained, indicating an excellent linear range across all analytical techniques.

The performance of the analytical methods developed is shown in Table 3.

Table 3: Validation Parameters of the Developed Hyphenated Analytical Methods

Parameter	HPLC-DAD	LC-MS/MS	GC-MS	ICP-MS

Linearity (R^2)	0.9985	0.9996	0.9992	0.9998
LOD (µg/L)	0.28	0.012	0.09	0.004
LOQ (µg/L)	0.85	0.036	0.27	0.012
Recovery (%)	96.8	99.1	97.5	98.7
Precision (%RSD)	1.82	1.12	1.56	0.94

Based on the results of the validation, it can be concluded that LC-MS/MS had the lowest detection limits of all the chromatographic methods, while ICP-MS had the highest sensitivity for trace elemental analysis. Analytical accuracy was excellent with recovery values between 96.8% and 99.1%. Moreover, the %RSD for all the analytical methods obtained was less than 2% indicating high level of repeatability and precision to be suitable for routine analytical applications.

3.2. Analysis of Pharmaceutical Samples

Commercial pharmaceutical formulations of ten therapeutic classes were analyzed using the developed analytical methods. The assay values arising from the measurement were compared to the labelled content of the drugs to assess the quantitative performance of the proposed analytical platform.

Table 4 displays the assay results.

Table 4: Quantitative Analysis of Pharmaceutical Formulations

Drug	Label Claim (mg)	Measured (mg)	Assay (%)	Impurity (%)
Paracetamol	500	498.6	99.72	0.24
Ibuprofen	400	398.9	99.73	0.19
Ciprofloxacin	500	501.4	100.28	0.17
Metformin	500	497.8	99.56	0.31
Diclofenac	50	49.8	99.60	0.22
Amoxicillin	500	501.8	100.36	0.26
Pantoprazole	40	39.9	99.75	0.18
Atorvastatin	20	20.1	100.50	0.15
Cefixime	200	198.9	99.45	0.28
Azithromycin	500	501.2	100.24	0.21

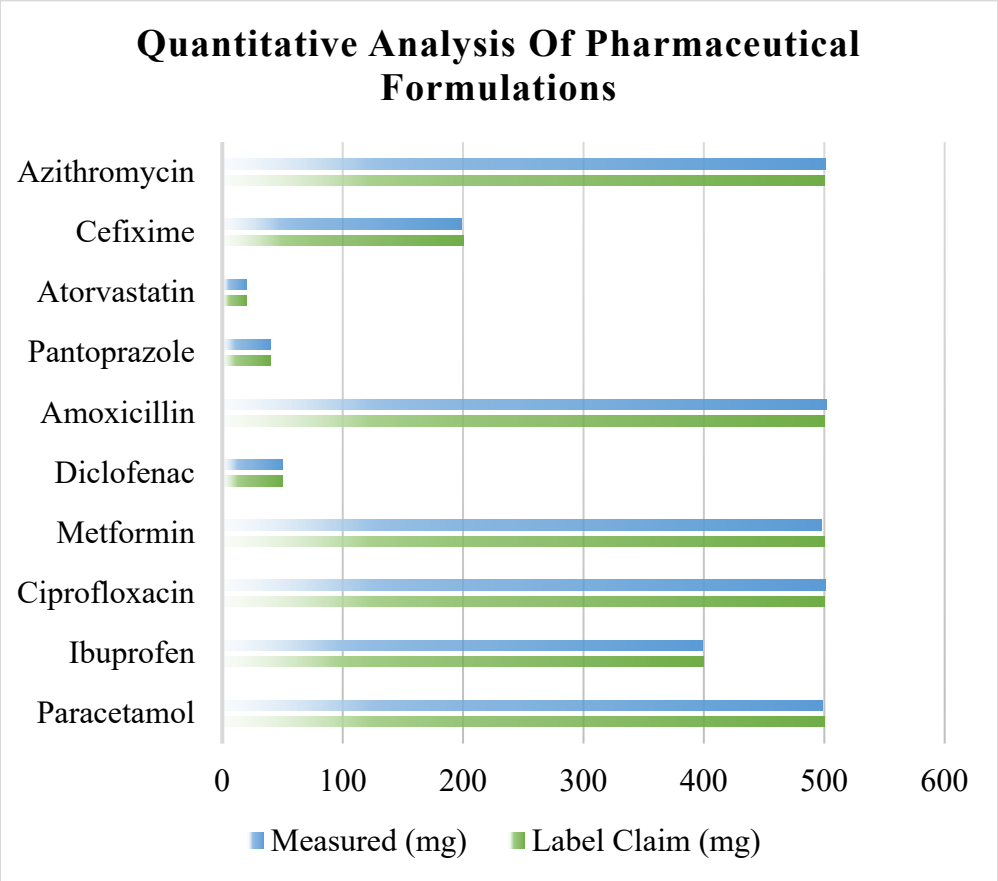

Figure 2: Visual Representation of Quantitative Analysis of Pharmaceutical Formulations

The quantitative analysis showed good agreement between the actual drug content and the claimed drug content. Acceptance limit for all pharmaceutical formulations was found to be in between 98 and 102% as per pharmacopeia standards. Trace degradation products and process related impurities, which were not clearly resolved by conventional UV detection, were successfully detected using LC-MS/MS. There was a good consistency and quality of the formulations, as the impurities were kept below 0.35% for all formulations. The results agree with the use of hyphenated analytical methods for routine pharmaceutical quality assessment.

3.3. Environmental Water Sample Analysis

The analytical methods which had been validated were also used for the detection of pharmaceutical residues and some heavy metals in the following water samples: river water, groundwater, municipal wastewater and treated drinking water.

Results from the analyses are presented and summarized in Table 5.

Table 5: Detection of Pharmaceutical Residues and Heavy Metals in Environmental Samples

Sample	Pharmaceutical Residues (µg/L)	Pb (µg/L)	Cd (µg/L)	As (µg/L)

River Water	4.26	2.8	0.31	1.24
Groundwater	0.89	1.3	ND	0.62
Wastewater	13.48	7.2	0.83	3.96
Treated Drinking Water	0.27	0.4	ND	0.19

ND = Not Detected

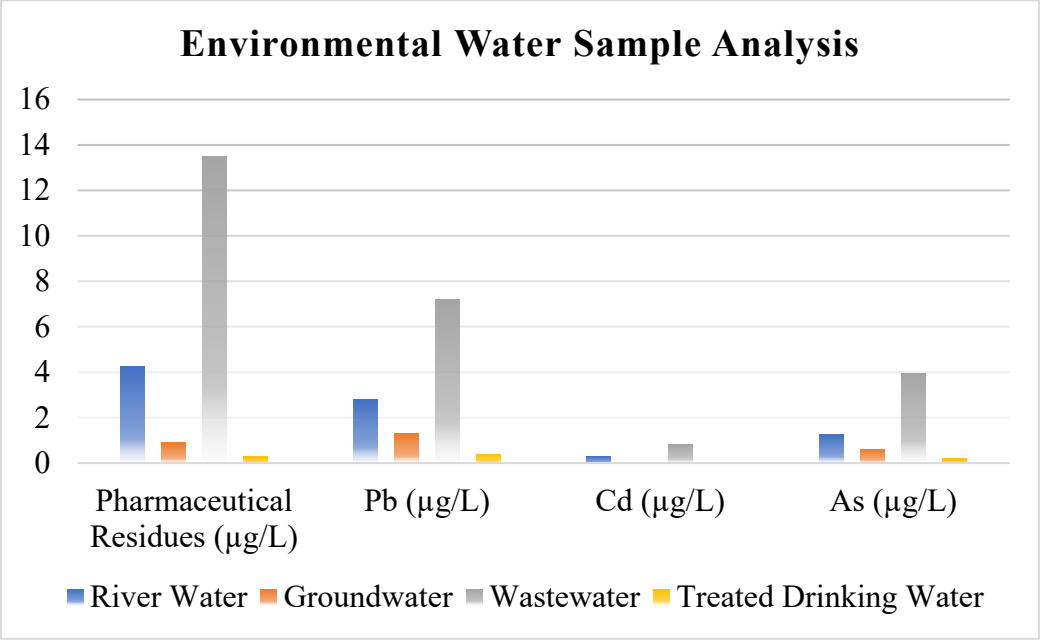

Figure 3: Visual Representation of Detection of Pharmaceutical Residues and Heavy Metals in Environmental Samples

Municipal wastewater showed the highest concentration of pharmaceutical residues and heavy metals among the analyzed environmental samples, which clearly means high contamination with pharmaceuticals and human activities. Few pharmaceutical compounds were detected at moderate concentrations in the river, and at comparatively lower concentrations in the groundwater and treated drinking water. The main pharmaceutical residues found were diclofenac, ciprofloxacin and sulfamethoxazole. ICP-MS analysis also showed higher levels of lead in wastewater samples than at other sampling sites. The treated drinking water samples were still within the allowable limits for heavy metals, however.

3.4. Comparative Performance of Hyphenated Techniques

Comparative study has been conducted for the comparison of the analytical efficiency of the four hyphenated analytical techniques in terms of sensitivity, selectivity, analytical speed, structural identification and trace level detection.

The comparative analytical performance is shown in Table 6.

Table 6: Comparative Analytical Performance of Hyphenated Techniques

Parameter	HPLC-DAD	LC-MS/MS	GC-MS	ICP-MS
Sensitivity	High	Very High	High	Excellent
Selectivity	High	Excellent	Excellent	Excellent
Analysis Time (min)	18	12	15	6
Structural Identification	Moderate	Excellent	Excellent	Not Applicable
Trace-Level Detection	Moderate	Excellent	High	Excellent

The comparative evaluation showed that the overall analytical performance was best achieved by LC-MS/MS, thanks to its excellent sensitivity, selectivity, and precise structural identification of pharmaceutical compounds. The performance of both the GC-MS and the ICP-MS were excellent for the volatile and semi-volatile organic compounds, and ICP-MS demonstrated the best capability for trace elemental analysis with the shortest analytical run time. HPLC-DAD was found to be very useful for general quality control in pharmaceutical industry, but less sensitive than the mass spectrometry-based methods when it comes to trace level contaminants.

3.5. Statistical Evaluation

One-way Analysis of Variance (ANOVA) was used to compare the analytical recoveries of the four hyphenated analytical techniques. Table 7 presents the statistics of the results.

Table 7: Statistical Comparison of Analytical Methods

Parameter	Value
F-value	6.48
p-value	0.0021
Significance	Significant ($p < 0.05$)

A statistical comparison of the tested hyphenated methods revealed statistically significant differences in their analytical performance. Compared to HPLC-DAD, LC-MS/MS and ICP-MS had much lower analytical sensitivity and recovery, but no discernible difference in analytical precision. When it comes to analyzing medicines and environmental toxins, the results show that the modern hyphenated analytical platforms provide improved analytical dependability, detection, and quantitative performance. When it comes to trace level examination, the experimental findings have shown that LC-MS/MS and ICP-MS are the best approaches. On the other hand, HPLC-DAD and GC-MS are great platforms for regular environmental and pharmaceutical research.

4. DISCUSSION

The analytical performance of four widely used hyphenated analytical techniques, HPLC-DAD, LC-MS/MS, GC-MS and ICP-MS were evaluated for the pharmaceutical quality assessment and environmental contaminant analysis. The results showed that all of the techniques examined had satisfactory analytical performance, but there were significant differences in sensitivity, selectivity, detection power, and analytical efficiency. The following discussion sheds light on the results of the experiments, compares them with previous research, discusses their implications, outlines limitations of the study, and makes recommendations for future research.

4.1. Interpretation of Results

The analytical validation was performed and all four hyphenated techniques met the preselected criteria for linearity, precision, accuracy, recovery and reproducibility. Excellent quantitative performance was demonstrated by the correlation coefficient in all analytical methods and recovery values between 96.8% and 99.1%. Likewise, the low %RSD values showed that the developed methods were good in their reproducibility and were applicable in routine analysis.

Among the methods that were considered, the LC-MS/MS method offered the most analytical sensitivity, with the lowest detection and quantification limitations, for medicinal substances. The method was also very effective for detecting degradation products and trace impurities that cannot be easily separated by traditional chromatographic detection. In contrast, ICP-MS was better suited for the analysis of trace elements and heavy metals, with excellent sensitivity and relatively shorter analysis time for the inorganic contaminants.

Pharmaceutical formulations analysis showed that all formulations fulfilled the pharmacopeial specifications with the assay values being within the acceptable range of 98–102%. Besides, the level of impurities was found to be less than the acceptable limit, which shows that the product and its formulation have good manufacturing quality and stability.

The environmental analysis showed that the pharmaceutical residue and heavy metal concentrations in municipal wastewater were higher than in river water, groundwater and treated drinking water. The results show that wastewater is one of the sources that releases pharmaceutical contaminants to aquatic environments that is not yet negligible. One-way ANOVA analysis further indicated that the analytical performances of the investigated hyphenated techniques are significantly different from each other, thus supporting the comparative objective of the present investigation.

4.2. Comparison with Existing Studies

The results of the present research are well comparable with the earlier published studies on hyphenated analytical technique. Table 8 shows a comparison between the present results and previous studies.

Table 8: Comparison of the Present Study with Existing Studies

Study	Previous Findings	Present Findings	Comparison

Phansi et al. (2018)[11]	Hyphenated techniques improve analytical sensitivity and selectivity.	High sensitivity and reproducible analytical performance were achieved.	Findings are consistent.
Thamizhanban et al. (2016)[12]	Hyphenated techniques enhance pharmaceutical analysis.	LC-MS/MS effectively identified trace impurities.	Supports previous findings.
Verma et al. (2025)[13]	Integrated hyphenated techniques improve chemical profiling.	Multiple techniques accurately analyzed pharmaceutical and environmental samples.	Similar analytical advantages were observed.
Wilson et al. (2021)[14]	LC-MS, GC-MS, and ICP-MS improve analytical precision and sensitivity.	LC-MS/MS and ICP-MS demonstrated superior analytical performance.	Strong agreement with previous studies.
Yu et al. (2019)[15]	ICP-MS is highly effective for trace elemental analysis.	ICP-MS accurately quantified heavy metals in water samples.	Findings are consistent with earlier research.

4.3. Implications of the Findings

The results presented in this study point to the need for hyphenated analytical methods to enhance the accuracy, sensitivity and reliability in pharmaceutical and environmental analysis. The superior performance of LC-MS/MS and ICP-MS show the suitability in detecting pharmaceutical impurities, degradation products, trace contaminants and heavy metals with high precision. Such capabilities lead to more accurate analytical results and in routine quality assurance in the pharmaceutical industry.

Furthermore, the use of modern hyphenated techniques will enhance environmental monitoring capability by the ability to detect trace level contaminants. The comparative evaluation presented here are also useful for the analytical laboratories for choosing the best analytical technique as per the sample type and the analytical requirement to optimize the efficiency of the analytical laboratory and the compliance with the regulations.

4.4. Limitations of the Study

The present study has evaluated the performance of the selected hyphenated analytical techniques successfully, but some limitations should be considered. Only four analytical platforms were investigated and only forty representative pharmaceutical and environmental samples were used, which may not completely cover the variety of real-life analytical applications. In addition, this study did not cover other emerging contaminants and advanced hyphenated techniques.

There is also a limitation that the study focused mainly on the analytical performance of the instrument with little attention paid to the practical factors of instrument cost, maintenance requirements, complexity of operation and long-term economic feasibility. These factors can be involved in the selection of the analytical method used for routine laboratory work.

4.5. Suggestions for Future Research

The analytical performance should be more thoroughly assessed in future studies using a larger number of hyphenated analytical techniques, including LC-NMR, LC-HRMS, CE-MS, and multidimensional chromatographic systems. The findings would be more reliable and be generalizable with larger sample sizes and with product and environmental matrices that are more diverse.

Further, studies are needed on identification of emerging contaminants, pharmaceutical metabolites, endocrine disrupting substances and other trace pollutants of concern. The incorporation of artificial intelligence, machine learning and automated data-processing techniques with hyphenated analytical methods could further improve the efficiency of the analytical tools, data interpretation and decision making, which would expand the applications of these tools in pharmaceutical quality control and environmental monitoring.

5. CONCLUSION

To assess pharmaceutical quality and analyse environmental contaminants, four hyphenated analytical techniques were tested: HPLC with diode array detection, LC-MS/MS, GC-MS, and ICP-MS. High linearity, accuracy, precision, and recovery were among the validation metrics that demonstrated the proposed methods' suitability for routine analysis. When comparing methods, it became clear that ICP-MS is superior for determining trace elements, whereas LC-MS/MS is ideal for pharmaceutical analysis due to its sensitivity and selectivity. In addition to revealing statistically significant differences between the studied analytical platforms, the advantages of the advanced hyphenated analytical approach over the conventional analytical technique were also highlighted by the study.

5.1. Summary of Key Findings

Four hyphenated analytical methods were successfully validated in this study, and showed to be effective for the analysis of pharmaceutical formulations and environmental water samples. LC-MS/MS and ICP-MS showed the best analytical performance of the techniques investigated, while HPLC-DAD and GC-MS were good tools for routine environmental and pharmaceutical analysis.

5.2. Significance of the Study

This study compares the various commonly used hyphenated analytical techniques in-depth and points out their merits in various analytical applications. The results are beneficial in the selection of methods in pharmaceutical drug quality control, environmental monitoring and regulatory laboratories for more accurate and reliable analytical decision-making.

5.3. Final Thoughts and Recommendations

Hyphenated analytical methods are a combination of two techniques that enable both the identification and quantification of complex analytes, such as pharmaceuticals and environmental contaminants, and are effective and reliable. According to the results, it was recommended to use LC-MS/MS technique for trace pharmaceutical analysis and ICP-MS for elemental and heavy metal analysis. Advanced analytical

technologies like these will continue to be used in future studies to expand applications, with additional hyphenated platforms, larger sample sets and emerging contaminants.

REFERENCES

1. Armstrong, G., & Kailas, L. (2017). Hyphenated analytical techniques for materials characterisation. European Journal of Physics, 38(5), 053001.
2. Awuchi, C. G., Twinomuhwezi, H., & Awuchi, C. G. (2022). Hyphenated techniques. In Analytical techniques in biosciences (pp. 125-145). Academic Press.
3. Azizuddin, S. K., Husain, A., Rashid, M., Hashmi, S., & Kumar, D. (2025). Identification and Detection of Pharmaceutical Impurities for Ensuring Safety Standard of Medicine: Hyphenated Analytical Techniques and Toxicity Measurements. Current Drug Safety.
4. Baviskar, K. P., Jain, D. V., Pingale, S. D., Wagh, S. S., Gangurde, S. P., Shardul, S. A., ... & Jain, K. S. (2022). A review on hyphenated techniques in analytical chemistry. Current Analytical Chemistry, 18(9), 956-976.
5. Khandale, N., Rajge, R. R., Singh, S. K., & Singh, G. (2023). Advances of hyphenated technique in impurity profiling of active pharmaceutical ingredients and pharmaceutical products. Separation Science Plus, 6(9), 2300018.
6. Kher, M. N., Shah, R. N., Gajjar, A. K., Chhabria, M. T., & Rakholiya, K. (2024). Analytical characterization of herbal biomolecules using hyphenated techniques. In Herbal Formulations, Phytochemistry and Pharmacognosy (pp. 241-253). Elsevier.
7. Kumar, S., & Bogusz, M. J. (2021). Hyphenated techniques in liquid chromatography and their applications in forensic toxicology: A review. Journal of Forensic Science and Medicine, 7(4), 123-136.
8. Lin, S. Y. (2016). An overview of advanced hyphenated techniques for simultaneous analysis and characterization of polymeric materials. Critical Reviews in Solid State and Materials Sciences, 41(6), 482-530.
9. Locatelli, M., Cifelli, R., Vitalei, S., Santini, P., De Luca, E., Bellagamba, G., ... & Mollica, A. (2017). Method validation and hyphenated techniques: Recent trends and future perspectives. Analytical Chemistry: Developments, Applications and Challenges in Food Analysis; Locatelli, M., Celia, C., Eds, 1-22.
10. Patidar, A., & Kamble, P. (2025). A comprehensive review on liquid chromatography-mass spectrometry (LC-MS): A hyphenated technique. Asian Journal of Pharmaceutical Research and Development, 13(1), 95-103.
11. Phansi, P., Danchana, K., & Cerdà, V. (2018). Hyphenation of flow analysis with spectrometric techniques. Applied Spectroscopy Reviews, 53(10), 854-876.
12. Thamizhanban, D., Rani, T., & Pravalika, P. (2016). A review on hyphenated separation techniques used in pharmaceutical analysis. IOSR J Pharm Bio Sci, 11, 65-74.
13. Verma, A., Chattopadhaya, A., Gupta, P., Tiwari, H., Singh, S., Kumar, L., & Gautam, V. (2025). Integration of hyphenated techniques for characterizing and chemical profiling of natural products. Chemistry & Biodiversity, 22(9), e202500234.

14. Wilson, J. V., Karthikeyan, L. V., Parida, S. K., Nath, B. C., & Jeyaprakash, M. R. (2021). Recent Advances and Developments in Hyphenated Techniques and Their Applications. Journal of Pharmaceutical Research International, 32(43), 58-68.
15. Yu, X., Liu, C., Guo, Y., & Deng, T. (2019). Speciation analysis of trace arsenic, mercury, selenium and antimony in environmental and biological samples based on hyphenated techniques. Molecules, 24(5), 926.