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Review Article

Recent Advances In Analytical Chemistry: Emerging Technologies, Innovative Methodologies And Sustainable Approaches In Pharmaceutical Analysis

Pogula Sathwika, Gope Bhargavi, Abijith Vardhan Reddy , Orsu Devadasu ,Darla Swarnalatha *

Malineni Perumallu Pharmacy College, Pulladigunta[V], Guntur, A.P, India

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ABSTRACT

Analytical chemistry plays an essential role in the identification, separation, quantification, and characterization of pharmaceutical substances. Recent technological developments have introduced advanced analytical approaches with improved sensitivity, accuracy, selectivity, speed, and reliability.[1] This review focuses on recent research in chromatography, mass spectrometry, spectroscopy, biosensors, Artificial Intelligence and Machine Learning (AI/ML), and Green Analytical Chemistry. Modern chromatographic and mass spectrometric techniques enable efficient separation, structural characterization, impurity profiling, and sensitive analysis of complex samples. Spectroscopic techniques provide rapid and non-destructive characterization, while biosensors offer sensitive, rapid, and potentially portable detection systems. AI/ML approaches are increasingly applied for analytical data processing, prediction, pattern recognition, and method optimization. Green analytical approaches aim to minimize hazardous solvents, waste generation, energy consumption, and sample requirements while maintaining analytical performance.[2] The review compares the methodologies, major findings, strengths, limitations, and research gaps reported in recent studies. Overall, the integration of advanced instrumentation, intelligent data analysis, biosensing technologies, and sustainable analytical practices is expected to contribute to the development of faster, more sensitive, reliable, automated, and environmentally sustainable pharmaceutical analytical methods.[1,2].

INTRODUCTION

Recent advances in analytical chemistry have significantly improved the identification,

separation, quantification, and characterization of pharmaceutical compounds.[3] Modern analytical techniques provide better sensitivity, accuracy,

***Corresponding Author:** Darla Swarnalatha.

Address: Malineni Perumallu Pharmacy College, Pulladigunta[V], Guntur, A.P, India

Email ✉: darlaswarnalatha@gmail.com

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selectivity, speed, and reliability compared with conventional methods. Chromatography and mass spectrometry are widely used for separation, identification, impurity profiling, and quantitative analysis,^[4] while spectroscopic techniques provide rapid and non-destructive molecular characterization.

In addition, biosensors have emerged as rapid and portable approaches for detecting drugs and biological analytes. The integration of Artificial Intelligence and Machine Learning (AI/ML) has further enhanced analytical data processing, pattern recognition, prediction, and method development. At the same time, Green Analytical Chemistry focuses on reducing hazardous solvents, waste, energy consumption, and sample requirements while maintaining analytical performance.

Therefore, the present literature review focuses on recent research in chromatography, mass spectrometry, spectroscopy, biosensors, AI/ML, and green analytical chemistry, highlighting their methodologies, major findings, advantages, limitations, and future research opportunities.^[3,4]

RECENT RESEARCH EVIDENCES:

1.CHROMATOGRAPHIC METHODS:

Mahdi et al. (2025) Reviewed HPLC applications in biopharmaceutical analysis. The technique was used for separation and characterization of complex biomolecules. HPLC supports quality assessment of proteins and monoclonal antibodies. Challenges in biopharmaceutical HPLC analysis were also discussed.^[5]

Pawar and Patel (2025) Developed a green RP-HPLC method for erlotinib impurity profiling. The method showed good accuracy, precision, sensitivity and robustness. It achieved effective

separation of the target impurity. The method also supported environmentally sustainable analysis.^[6]

Polshettiwar et al. (2025) Developed an RP-HPLC method for analysis of teriflunomide. Forced degradation studies were performed under different stress conditions. HRMS was used to identify and characterize degradation impurities. The study demonstrated effective chromatographic stability assessment.^[7]

Wei et al. (2025) Reviewed HILIC and mixed-mode chromatography in pharmaceutical analysis. These techniques are useful for polar and charged pharmaceutical compounds. They provide complementary separation to conventional RP-HPLC. Their application in complex pharmaceutical analysis is increasing.^[8]

Ntorkou & Zacharis (2025) Reviewed HILIC applications in pharmaceutical impurity profiling. HILIC improves separation of highly polar impurities. It can also be coupled with MS for sensitive impurity characterization. The study highlighted HILIC as a complementary chromatographic technique.^[9]

Guillarme et al. (2025) Reviewed recent developments in liquid chromatography for pharmaceutical analysis. Advances in stationary phases and separation technologies improve analytical efficiency. Modern LC enables faster and better separation of complex samples. The field continues to develop toward efficient pharmaceutical analysis.^[10]

Prasad et al. (2024) Developed a UHPLC method for quantifying nilotinib and related impurities. QbD was used to optimize chromatographic conditions. The method provided rapid separation with good precision and sensitivity. It demonstrated UHPLC suitability for pharmaceutical impurity analysis.^[11]



Table -1

S. NO	Author & year	Analyte	Methodology	Key findings	Research gap
1.	Mahdi et al., 2025	Proteins and monoclonal antibodies	HPLC-based biopharmaceutical analysis	HPLC supports separation, characterization and quality assessment of complex biomolecules.	Improved methods are required for highly complex biopharmaceutical samples.
2.	Pawar & Patel, 2025	Erlotinib and desethynyl erlotinib	Green RP-HPLC for impurity profiling	Good accuracy, precision, sensitivity and robustness with reduced environmental impact.	More green chromatographic methods should be developed for pharmaceutical analysis.
3.	Polshettiwar et al., 2025	Teriflunomide and degradation impurities	RP-HPLC with forced degradation and HRMS	Effective separation and characterization of degradation-related impurities.	Further LC–HRMS/MS studies are needed for detailed impurity confirmation.
4.	Wei et al., 2025	Polar and charged pharmaceutical compounds	HILIC and mixed-mode chromatography	Improved separation of polar analytes compared with conventional RP-HPLC.	More applications are needed for complex pharmaceutical and new drug modalities.
5.	Ntorkou & Zacharis, 2025	Pharmaceutical impurities	HILIC-based impurity profiling	HILIC provides better retention of highly polar impurities and can be coupled with MS.	Standardized HILIC methods for routine impurity profiling need further development.

6.	Guillarme et al., 2025	Pharmaceutical compounds and complex samples	Advanced liquid chromatography techniques	New stationary phases and LC technologies improve separation efficiency and analysis speed.	Further development of high-efficiency, rapid and sustainable LC approaches is required.
7.	Prasad et al., 2024	Nilotinib and related impurities	UHPLC with QbD-based optimization	Rapid separation with good precision, sensitivity and impurity detection.	More rapid and robust UHPLC methods are needed for routine impurity analysis.

2.MASS SPECTROMETRIC METHODS

Bhalekar and Shah (2025) developed an LC-HRMS method for the analysis of nusinersen using an AQbD approach. The method provided accurate and reliable quantification of the drug and its impurities. It demonstrated the usefulness of HRMS for complex pharmaceutical analysis.^[12]

Kodidasu et al. (2025) applied HRMS for the absolute quantification of coeluting impurities in glucagon. The technique enabled detection and quantification of low-level peptide impurities. The study highlighted HRMS for characterization of peptide drugs.^[13]

Heide et al. (2025) developed a rapid HRMS-based method for active pharmaceutical ingredient screening. The approach allowed fast analysis of pharmaceutical products with reduced sample preparation. It demonstrated the potential of ambient MS for pharmaceutical quality control.^[14]

Guo et al. (2025) developed an online SPE-LC-MS/MS method for simultaneous determination of sacubitril and seven sartans in serum. The method

provided sensitive and selective analysis of multiple drugs. It showed the application of MS/MS in bioanalytical studies.^[15]

Jiang et al. (2025) developed an LC-MS/MS method for simultaneous determination of busulfan, fludarabine, phenytoin and posaconazole in plasma. The method required a small sample volume and a short analysis time. It was successfully applied to therapeutic drug monitoring.^[16]

Lee et al. (2025) developed LC-MS/MS and HRMS methods for detecting genotoxic nitrosamine impurities in sitagliptin/metformin tablets. The methods enabled sensitive monitoring of potentially harmful impurities. The study demonstrated the importance of MS in pharmaceutical quality control.^[17]

Vo and Maeng (2025) reviewed MS-based bioanalytical methods for endogenous biomarkers related to drug–drug interactions. LC-MS/MS provides high sensitivity and selectivity for biomarker analysis. The study emphasized the



growing role of MS in drug development and bioanalysis.^[18]

Table 2

S. NO	Author & year	Analyte	Methodology	Key findings	Research gap
1.	Bhalekar & Shah (2025)	Nusinersen	LC-HRMS with AQBd	Accurate drug and impurity quantification	Further application to other oligonucleotides
2.	Kodidasu et al. (2025)	Glucagon impurities	LC-HRMS	Quantified coeluting peptide impurities	More peptide drugs need evaluation
3.	Heide et al. (2025)	Pharmaceutical APIs	Plasma-based desorption/ionization HRMS	Enabled rapid API screening	Broader pharmaceutical application required
4.	Guo et al. (2025)	Sacubitril and 7 sartans	Online SPE-LC-MS/MS	Simultaneous determination in serum	Application to larger clinical populations
5.	Jiang et al. (2025)	Busulfan, fludarabine, phenytoin, posaconazole	LC-MS/MS	Rapid simultaneous plasma analysis	Wider therapeutic drug-monitoring studies
6.	Lee et al. (2025)	Nitrosamine impurities	LC-MS/MS and HRMS	Sensitive detection of genotoxic impurities	More drug combinations and impurities should be investigated
7.	Vo & Maeng (2025)	Endogenous biomarkers	LC-MS/MS-based bioanalysis	Improved biomarker measurement for drug–drug interactions	More validated biomarkers needed for clinical use

3. OTHER SPECTROSCOPIC METHODS

Xia et al. (2025) investigated surface-enhanced Raman spectroscopy (SERS) for pharmaceutical

analysis. The technique enables sensitive identification of drug components at low concentrations. It provides molecular-level information with minimal sample preparation.



Substrate reproducibility and data processing remain challenges.^[19]

Liu et al. (2025) explored the combination of Raman spectroscopy with artificial intelligence for analytical applications. AI improves spectral processing, feature extraction and compound identification. The approach can increase the speed and accuracy of Raman analysis. Large datasets and computational requirements remain limitations.^[20]

Mocarska et al. (2025) evaluated ATR-FTIR spectroscopy and X-ray powder diffraction for pharmaceutical product analysis. These techniques provide rapid chemical identification and solid-state characterization. They can assist in screening pharmaceutical products. Broader validation is needed for routine applications.^[21]

Al-Majed et al. (2025) reviewed UV-Vis, FTIR, Raman, SERS, NMR and terahertz spectroscopy in pharmaceutical and biomedical analysis.

Spectroscopic methods enable rapid and often non-destructive characterization. Their combination with chemometrics improves analytical interpretation. Instrument cost and complex data analysis can limit implementation.^[22]

Tang et al. (2024) reviewed Raman spectroscopy and Raman imaging in pharmaceutical analysis. These techniques support drug identification, formulation analysis and process monitoring. They offer rapid and non-destructive measurements. Improving sensitivity and analytical throughput remains necessary.^[24]

Shah et al. (2023) reviewed applications of Raman spectroscopy in pharmaceutical analysis. Raman techniques can characterize drug composition, molecular structure and solid-state properties. SERS improves sensitivity for low-level analytes. Standardization and quantitative analysis remain challenges.^[25]

Table -3

S.NO	Author & year	Analyte	Methodology	Key findings	Research gap
1.	Xia et al. (2025)	Pharmaceutical compounds	SERS	Enabled sensitive identification of drug components at low concentrations	Improved and standardized SERS substrates are needed
2.	Liu et al. (2025)	Biomedical samples	Raman + AI	AI improved spectral processing and compound identification	More validated AI models are needed
3.	Mocarska et al. (2025)	Medicinal/falsified products	ATR-FTIR + XRPD	Enabled rapid chemical identification and solid-state characterization	Further validation for routine screening



4.	Al-Majed et al. (2025)	Pharmaceutical & biomedical samples	UV-Vis, FTIR, Raman, SERS, NMR, THz	Spectroscopy provided rapid and often non-destructive characterization	Greater integration with chemometrics needed
5.	Tang et al. (2024)	Pharmaceutical formulations	Raman spectroscopy & imaging	Supported drug identification, formulation analysis and process monitoring	Higher sensitivity and throughput required
6.	Shah et al. (2023)	Drugs and pharmaceutical products	Raman spectroscopy	Characterized composition, structure and solid-state properties	Better standardization and quantitative methods needed

4. BIOSENSOR METHODS

Sanko et al. (2026) reviewed electrochemical multi-drug biosensing approaches. Nanomaterials and electrochemical techniques support simultaneous detection of different drugs. Multi-analyse sensing can benefit pharmaceutical and therapeutic monitoring. Selectivity, stability and practical implementation require further research.^[26]

Ganesan et al. (2025) reviewed advanced electrochemical biosensors for drug detection. Nanomaterials, artificial intelligence and wearable technologies can improve sensor performance. These systems may enable real-time drug monitoring. Sensor reliability and clinical validation remain challenges.^[27]

Zabitlet et al. (2025) reviewed electrochemical sensors for analytes in blood, plasma, serum, saliva, sweat and urine. These sensors offer rapid response, low sample requirements and portability. Nanomaterials can improve sensitivity and selectivity. Therapeutic monitoring is an important potential application.^[28]

Liu et al. (2024) developed a wireless electrochemical aptamer-based biosensor for tobramycin detection. The sensor used miniaturised electrodes for drug monitoring. It demonstrated potential for rapid and portable analysis. The approach may be useful for point-of-care drug monitoring.^[29]

Chang et al. (2024) developed an electrochemical aptasensor for methylamphetamine detection. A competitive DNA-based sensing strategy was used for selective drug recognition. The sensor provided rapid electrochemical detection. It showed potential for portable drug-screening applications.^[30]

Zhang et al. (2024) developed an electrochemical aptamer biosensor for Δ^9 -THC detection in biofluids. A modified gold electrode improved sensing performance and antifouling properties. The sensor achieved sensitive detection at low concentrations. It demonstrated potential for analysis of complex biological samples.^[31]

Amhamdi et al. (2023) reviewed electrochemical sensors and biosensors for drugs and metabolites.



Nanomaterials such as graphene, carbon sensitive analysis. They have applications in nanotubes and nanoparticles can enhance sensor pharmaceutical and biological analysis.^[32] performance. These systems provide rapid and

Table -5

S.NO	Author & year	Analyte	Methodology	Key findings	Research gap
1.	Sanko et al. (2026)	Multiple pharmaceutical drugs	Electrochemical multi-drug biosensing	Enabled simultaneous detection of different drug analytes	Improved multiplexing, stability and commercial application
2.	Ganesan et al. (2025)	Pharmaceutical drugs	Electrochemical biosensors + nanomaterials + AI/wearables	Integration of advanced technologies improved drug-detection capabilities	Clinical translation and sensor reliability
3.	Zabitlet et al. (2025)	Blood, plasma, serum, saliva, sweat and urine analytes	Electrochemical sensing platforms	Demonstrated potential for rapid monitoring in biological fluids	Improved wearable and real-time sensing
4.	Liu et al. (2024)	Tobramycin	Wireless electrochemical aptamer-based biosensor	Enabled rapid detection of tobramycin using a miniaturised sensing platform	Further validation in real clinical samples
5.	Chang et al. (2024)	Methylamphetamine	Electrochemical aptasensor with competitive DNA recognition	Provided selective and rapid detection of the target drug	Greater application to real biological samples
6.	Zhang et al. (2024)	Δ^9 -THC	Electrochemical aptamer sensor with modified gold electrode	Enabled sensitive THC detection in biofluids	Improved long-term stability and clinical validation

7.	Amhamdi et al. (2023)	Drugs and metabolites	Electrochemical sensors and biosensors	Nanomaterials improved sensitivity and analytical performance	Standardised and commercially scalable sensors
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5. AIML METHODS

Jain et al. (2026) discussed AI/ML applications in pharmaceutical analysis and quality control. AI can support impurity profiling, stability prediction and process monitoring. Integration with analytical technologies may improve real-time quality assessment. Regulatory compliance and model transparency remain challenges.^[33]

Cunha et al. (2025/2026) examined AI-driven data analysis in biopharmaceutical analysis. AI improves interpretation of complex analytical and multi-omics data. Integration with automation can enhance analytical efficiency. High costs, regulatory requirements and skilled-personnel needs remain limitations.^[34]

Srivastava and Nandan (2025) discussed AI applications in analytical chemistry and pharmaceutical analysis. AI/ML helps in spectral interpretation, analyte identification and quantification. It can process complex analytical datasets efficiently. Data quality and model interpretability remain challenges.^[35]

Hong et al. (2025) reviewed machine learning in small-molecule mass spectrometry. ML improves MS/MS spectral interpretation and compound

identification. It can help analyse complex spectra and overcome incomplete spectral libraries. Large datasets and model validation are still required.^[36]

Li et al. (2025) reviewed AI applications in drug discovery and development. AI supports target identification, molecular design, lead optimization and drug repurposing. It can accelerate analysis of large chemical and biological datasets. Data quality and regulatory concerns remain limitations.^[37]

Srivastava et al. (2025) reviewed AI/ML applications in analytical chemistry and pharmaceutical research. Machine learning supports classification, quantification and predictive modelling of analytical data. It can extract useful patterns from large datasets. Data heterogeneity and validation require further investigation.^[38]

Alves et al. (2025) reviewed AI/ML applications in HPLC method development. AI can assist chromatographic optimization and prediction of separation conditions. This may reduce experimental workload and development time. Standardization, interpretability and validation remain important research gaps.^[39]

Table -6

S.NO	Author & year	Analyte	Methodology	Key findings	Research gap
1.	Jain et al. (2026)	Pharmaceutical QC	AI/ML for impurity, stability and process analysis	Supported quality assessment	Greater regulatory acceptance



				and process monitoring	
2.	Cunha et al. (2025/26)	Biopharmaceutical analysis	AI-driven analytical data processing	Improved interpretation of complex analytical and multi-omics data	Integration into routine QC
3.	Srivastava & Nandan (2025)	Analytical & pharmaceutical analysis	AI/ML and chemometrics	Improved spectral interpretation, identification and quantification	More validated models needed
4.	Hong et al. (2025)	Small-molecule analysis	ML with mass spectrometry	Improved MS/MS spectral interpretation and compound identification	Better model validation and spectral libraries
5.	Li et al. (2025)	Drug discovery & development	AI/ML predictive modelling	Supported target identification, molecular design and lead optimization	Improved interpretability and clinical validation
6.	Srivastava et al. (2025)	Analytical chemistry	AI/ML and predictive modelling	Supported classification, quantification and data interpretation	Robust and transferable models
7.	Alves et al. (2025)	HPLC method development	AI/ML-assisted chromatographic optimization	Assisted prediction and optimization of separation conditions	Standardized and interpretable models

6. GREEN ANALYTICAL METHODS:

Rahman et al. (2026) reviewed green approaches for pharmaceutical impurity profiling. Green

chromatography, spectroscopy, microextraction and miniaturisation were discussed. Greenness metrics such as AGREE can assess environmental



performance. Cost, reproducibility and regulatory requirements remain challenges.^[40]

Mehta et al. (2025/2026) reviewed GAC applications in pharmaceutical analysis and environmental monitoring. Reduction of toxic reagents, solvents, energy consumption and sample preparation was emphasized. Green methods can improve sustainability and analytical efficiency. Integration of emerging technologies remains a future direction.^[41]

Singh et al. (2025) reviewed green chromatographic and spectroscopic techniques in pharmaceutical chemistry. Miniaturisation and automation can reduce sample and reagent consumption. AI and real-time monitoring are emerging green approaches. Validation and implementation costs remain limitations.^[42]

Gamal et al. (2025) reviewed green chromatographic methods for pharmaceutical impurity analysis. Environmentally preferable solvents and chromatographic conditions were explored. These methods can reduce the

environmental impact of impurity testing. More selective and sustainable methods are needed.^[43]

Patil et al. (2025) discussed green LC methods and circular analytical chemistry. Eco-friendly solvents and microextraction approaches can reduce waste and resource consumption. The methods support more sustainable pharmaceutical analysis. Further practical implementation is required.^[44]

Ahmed et al. (2024) reviewed green liquid chromatography for pharmaceutical analysis. Eco-friendly solvents and reduced solvent consumption were discussed. Tools such as GAPI, NEMI, Eco-Scale and AGREE help evaluate greenness. Standardised assessment remains an important need.^[45]

Mehta et al. (2024) reviewed Green Analytical Chemistry in pharmaceutical analysis. Green solvents, miniaturisation and reduced sample preparation were highlighted. These approaches reduce solvent consumption and waste. The study emphasized sustainability without compromising analytical performance^[46]

Table -7

S.NO	Author & year	Analyte	Methodology	Key findings	Research gap
1.	Rahman et al. (2026)	Pharmaceutical impurity profiling	Green chromatography, spectroscopy and microextraction	Multiple green approaches reduced environmental burden	Better harmonisation and validation
2.	Mehta et al. (2025/26)	Pharmaceutical & environmental analysis	GAC and sustainable analytical techniques	Reduced toxic reagents, solvents, energy and sample preparation	Integration of emerging technologies

3.	Singh et al. (2025)	Pharmaceutical chemistry	Green chromatography & spectroscopy	Miniaturisation, automation and AI reduced resource consumption	More real-world industrial applications
4.	Gamal et al. (2025)	Pharmaceutical impurities	Green chromatography	Environmentally preferable solvents and conditions reduced environmental impact	More selective and sustainable methods
5.	Patil et al. (2025)	Pharmaceutical analysis	Green LC, microextraction and circular analytical chemistry	Reduced solvent, waste and energy consumption	More scalable green methods
6.	Ahmed et al. (2024)	Pharmaceutical analysis	Green LC + GAPI, NEMI, Eco-Scale, AGREE	Green solvents and reduced waste improved analytical greenness	Greater standardisation of metrics
7.	Mehta et al. (2024)	Pharmaceutical analysis	Green Analytical Chemistry (GAC)	Green solvents, miniaturisation and reduced sample preparation improved sustainability	Wider adoption of green methods

RESEARCH FINDINGS

Recent studies show that advanced analytical techniques have improved the sensitivity, accuracy, selectivity, and speed of pharmaceutical analysis.^[47]

Chromatography, mass spectrometry, and spectroscopy demonstrated effective separation, identification, quantification, and characterization of complex analytes.^[47]

Biosensors and AI/ML approaches enabled rapid detection, data processing, prediction, and analytical method optimization.

Green analytical approaches reduced solvent consumption, waste generation, energy use, and environmental impact, supporting more sustainable pharmaceutical analysis.^[48]

FUTURE PERSPECTIVES



Future analytical methods are expected to become faster, more sensitive, automated, and miniaturized for pharmaceutical analysis.^[49]

Integration of AI/ML with chromatography, mass spectrometry, spectroscopy, and biosensors can improve data interpretation and method development.^[49]

Greater use of green solvents, microfluidics, and low-waste techniques can make analytical procedures more sustainable.^[50]

Future research should focus on validated, cost-effective, portable, and integrated analytical platforms for real-world pharmaceutical applications.^[49,50]

CONCLUSION

Recent advances in analytical chemistry have improved the sensitivity, accuracy, speed, and reliability of pharmaceutical analysis.

Chromatography, mass spectrometry, spectroscopy, and biosensors provide diverse approaches for efficient detection and characterization of analytes.

AI/ML enhances analytical data processing and method development, while Green Analytical Chemistry promotes safer and more sustainable analytical practices.

Future integration of these technologies can lead to rapid, reliable, intelligent, and environmentally sustainable pharmaceutical analytical methods.

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