

Recent Advances and Applications of Analytical Techniques in Forensic Chemistry: Challenges and Future Perspectives

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Abstract

Forensic chemistry plays a crucial role in criminal investigations by analyzing physical evidence using advanced analytical techniques. This article highlights the importance of instrumental methods such as chromatography, spectroscopy, and mass spectrometry in forensic analysis. These techniques enable accurate identification and quantification of drugs, poisons, and unknown substances. Recent advancements have significantly improved sensitivity, selectivity, and reliability. This paper also discusses applications, challenges, and future perspectives in forensic chemical analysis. Forensic chemistry finds wide applications in areas such as toxicology, narcotics analysis, environmental forensics, and explosive residue detection. Despite these advancements, challenges such as sample contamination, complex matrices, limited sample availability, and the need for rigorous method validation persist. Future perspectives emphasize the development of rapid, non-destructive techniques, increased use of artificial intelligence and machine learning, and stronger quality assurance protocols to ensure accuracy and reproducibility in forensic investigations.

Keywords: Forensic chemistry, chromatography, spectroscopy, GC-MS, analytical techniques

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Introduction

Forensic chemistry is a vital branch of applied chemistry that focuses on the examination of chemical evidence in criminal investigations. It involves identifying unknown substances and interpreting analytical results scientifically [1]. With technological advancements, modern analytical instruments have enhanced the precision, sensitivity, and reliability of forensic investigations. Research in this field continues to evolve with improvements in instrumentation and methodology [2-3]. Recent studies demonstrate significant advancements in forensic analytical techniques. Rapid GC-MS methods have been developed for efficient drug screening [4], while high-resolution mass spectrometry enables detection of emerging substances [5-7]. Additionally, novel sample matrices such as hair and insects are increasingly used in forensic investigations [8].

Furthermore, advancements in spectroscopic techniques such as FTIR and Raman spectroscopy have enabled non-destructive and rapid on-site analysis of evidence [9, 10]. The development of portable and handheld analytical devices has further facilitated field-based investigations, reducing the time required for laboratory confirmation [11, 12].

Despite these advancements, challenges remain, including matrix interferences, limited sample quantities, and the need for standardized protocols and validation procedures [13-15]. Ongoing research is focused on improving detection limits, developing eco-friendly analytical methods, and incorporating artificial intelligence to strengthen forensic data analysis and decision-making [16-18].

Literature Review

Recent studies (2020–2025) indicate significant progress in analytical techniques used in forensic science. Advanced chromatographic and spectroscopic methods have improved detection limits and reduced analysis time. Studies highlight the integration of hyphenated techniques such as GC-MS and LC-MS for complex sample analysis. Researchers have also emphasized the importance of quality assurance and validation in forensic laboratories.

In addition, the adoption of high-resolution mass spectrometry (HRMS) and tandem mass spectrometric techniques has enabled the identification of novel psychoactive substances and trace-level contaminants with greater accuracy [19–21]. Emerging approaches such as ambient ionization techniques and microextraction methods have further simplified

sample preparation and enhanced analytical efficiency [22–24]. The incorporation of automation and digital technologies has streamlined laboratory workflows, improving reproducibility and throughput [25, 26].

Analytical Techniques in Forensic Chemistry

Chromatography

Chromatography is widely used for the separation, identification, and quantitative analysis of complex mixtures in forensic science. It is based on the differential distribution of analytes between a stationary phase and a mobile phase, allowing efficient separation of compounds with varying physicochemical properties [3, 27].

- **Gas Chromatography (GC):** Suitable for volatile and thermally stable compounds. It is commonly used in the analysis of drugs, alcohol, fire debris (arson cases), and toxic substances. When coupled with mass spectrometry (GC–MS), it provides high sensitivity and specificity for confirmatory analysis [13, 28].
- **High Performance Liquid Chromatography (HPLC):** Suitable for non-volatile, polar, and thermally labile compounds. It is extensively used in the detection of pharmaceuticals, poisons, and biomolecules in biological samples. Advanced variants such as UHPLC offer faster analysis with improved resolution and sensitivity [29, 30].

In addition, hyphenated techniques such as GC–MS and LC–MS/MS have become indispensable in modern forensic laboratories due to their ability to provide both qualitative and quantitative information with high accuracy [31, 32]. These methods are particularly valuable in trace-level detection and complex matrix analysis. Chromatographic techniques also play a crucial role in doping control, environmental forensics, and explosive residue analysis [33].

Despite their widespread application, challenges such as sample preparation, matrix interference, and the requirement for skilled operation remain [34]. Ongoing developments focus on miniaturization, automation, and the use of green solvents to enhance efficiency and sustainability in forensic chromatographic analysis [16].

Spectroscopy

Spectroscopic methods are essential for the structural identification and characterization of compounds in forensic science. These techniques are based on the interaction of electromagnetic radiation with matter, providing valuable information about molecular structure, functional groups, and chemical composition [3, 35].

- **UV–Visible Spectroscopy:** Primarily used for qualitative and quantitative analysis of substances based on their electronic transitions. It is widely applied in the analysis of drugs, dyes, and toxic compounds, especially for preliminary screening and concentration determination in solution [36].
- **Infrared (IR) Spectroscopy:** Used for functional group identification by measuring molecular vibrations. It is highly effective in identifying organic compounds, polymers, and narcotics. Fourier Transform Infrared (FTIR) spectroscopy, in particular, allows rapid and non-destructive analysis of solid and liquid samples [37, 38].

In addition, advanced spectroscopic techniques such as Raman spectroscopy complement IR analysis and enable non-destructive, in situ examination of forensic evidence, including explosives, inks, and fibers. These methods often require minimal or no sample preparation and can be applied directly at crime scenes using portable instruments [10].

Spectroscopic techniques are extensively used in questioned document examination, fiber analysis, paint identification, and counterfeit drug detection. Despite their advantages, limitations such as spectral interferences and overlapping peaks may affect accuracy, requiring complementary analytical methods for confirmation [9]. Ongoing developments focus on improving sensitivity, miniaturization of instruments, and integration with chemometric tools for enhanced data interpretation.

Mass Spectrometry

Mass spectrometry is a powerful tool for compound identification based on mass-to-charge ratio. GC–MS is widely used in forensic toxicology due to its high sensitivity and specificity [4]. Mass spectrometry is a powerful analytical tool used for the identification and characterization of compounds based on their mass-to-charge (m/z) ratio. It provides highly sensitive and selective detection, making it indispensable in forensic analysis. The technique involves ionization of chemical species, separation of ions according to their m/z ratio, and detection to generate a characteristic mass spectrum that serves as a molecular fingerprint [39, 40].

Gas Chromatography–Mass Spectrometry (GC–MS) is widely used in forensic toxicology due to its high sensitivity, specificity, and reliability. It is particularly effective for the analysis of volatile and semi-volatile compounds such as

drugs, alcohols, poisons, and fire debris residues. GC–MS is often considered the “gold standard” for confirmatory analysis in forensic laboratories [13, 28].

In addition, Liquid Chromatography–Mass Spectrometry (LC–MS/MS) is extensively used for the analysis of non-volatile, polar, and thermally labile compounds, including pharmaceuticals, metabolites, and emerging psychoactive substances. High-resolution mass spectrometry (HRMS) further enhances the capability to detect unknown compounds and trace-level contaminants with high accuracy [20, 31].

Mass spectrometry also plays a crucial role in areas such as doping control, explosive residue analysis, environmental forensics, and biological sample analysis [33]. Despite its advantages, challenges such as high instrument cost, complex data interpretation, and the need for skilled personnel remain [34]. Recent advancements focus on miniaturization, automation, and coupling with advanced data analysis tools, including artificial intelligence, to improve efficiency and reliability in forensic investigations [17, 25].

Applications of Forensic Chemistry

Forensic chemistry has wide-ranging applications in criminal investigations and public safety, providing scientific support for the identification and interpretation of chemical evidence [1, 9]. Its applications extend across multiple domains, including toxicology, environmental science, and regulatory analysis.

- **Drug identification and analysis:** Forensic chemistry plays a crucial role in the detection and characterization of illicit drugs, controlled substances, and new psychoactive compounds using techniques such as GC–MS and LC–MS/MS [14, 32].
- **Detection of poisons and toxic substances:** Toxicological analysis is essential in cases of poisoning, overdose, and suspicious deaths. Biological samples such as blood, urine, and tissues are analyzed to detect and quantify toxic agents [41].
- **Explosive residue analysis:** Forensic chemists analyze residues from explosives and incendiary devices to determine their composition and origin, aiding in criminal investigations and counter-terrorism efforts [42].
- **Food adulteration testing:** Chemical analysis is used to detect contaminants, adulterants, and harmful additives in food products, ensuring public health and safety [43].
- **Environmental forensic investigations:** Forensic techniques help identify sources of environmental pollution, such as oil spills, industrial waste, and toxic chemical releases, by analyzing soil, water, and air samples [44].

In addition, forensic chemistry is applied in areas such as doping control in sports, questioned document examination (ink and paper analysis) and trace evidence analysis (fibers, paints, glass). Recent advancements in analytical instrumentation and data analysis have further enhanced the accuracy, speed, and reliability of these applications. Despite its broad utility, challenges such as sample complexity, contamination risks, and legal admissibility of evidence require strict adherence to quality assurance and validation protocols [15].

Advantages of Analytical Techniques

Analytical techniques used in forensic chemistry offer several significant advantages that enhance the accuracy, efficiency, and reliability of criminal investigations [3, 45]. Continuous advancements in instrumentation have further strengthened their role in modern forensic laboratories.

- **High sensitivity and precision:** Modern analytical instruments can detect substances at trace and ultra-trace levels with high accuracy, enabling the identification of minute quantities of drugs, toxins, and explosives [31].
- **Rapid and accurate results:** Advanced techniques such as GC–MS, LC–MS/MS, and spectroscopic methods provide quick and reliable results, which are crucial for timely forensic investigations and legal proceedings [13].
- **Capability to analyze complex mixtures:** Chromatographic and hyphenated techniques allow effective separation and analysis of complex sample matrices, including biological fluids, environmental samples, and contaminated materials [32].
- **Reproducibility and reliability:** Standardized analytical protocols and validated methods ensure consistent and reproducible results, which are essential for the admissibility of forensic evidence in court [15].

In addition, many modern techniques are non-destructive or minimally destructive, preserving valuable evidence for further examination. The integration of automation and digital data processing has improved throughput and reduced human error. Furthermore, the use of hyphenated and high-resolution techniques enhances selectivity and confirmatory

analysis, increasing confidence in results. Despite these advantages, proper calibration, method validation, and skilled operation remain essential to maintain analytical integrity [14].

Challenges in Forensic Analysis

Despite significant advancements, forensic analysis faces several challenges that can affect the accuracy, reliability, and admissibility of results in legal contexts [1, 9]. Addressing these issues is essential for maintaining the integrity of forensic investigations.

- **Risk of sample contamination:** Improper collection, handling, or storage of evidence can lead to contamination, degradation, or loss of critical information, ultimately affecting analytical outcomes [2].
- **High cost of advanced instruments:** Sophisticated analytical instruments such as GC–MS, LC–MS/MS, and HRMS require substantial investment, maintenance, and infrastructure, limiting their availability in resource-constrained laboratories [13].
- **Requirement of skilled personnel:** Operation of advanced instruments and interpretation of complex data demand highly trained and experienced forensic experts, highlighting the need for continuous training and capacity building [25].
- **Legal and ethical constraints:** Forensic evidence must meet strict legal standards for admissibility in court. Issues such as chain of custody, method validation, accreditation, and ethical handling of evidence are critical to ensure credibility [15].

In addition, challenges such as matrix interferences, limited or degraded sample quantities, and lack of standardized protocols across laboratories can further complicate forensic analysis. Rapidly evolving synthetic drugs and new psychoactive substances also pose difficulties in detection and identification. Moreover, managing large volumes of analytical data requires robust data handling and cybersecurity measures. Ongoing efforts focus on improving standardization, enhancing quality assurance, and integrating advanced technologies such as artificial intelligence to overcome these limitations [14, 17].

Practical Insights from Forensic Laboratory Experience

In forensic laboratories, analytical techniques such as GC–MS and HPLC are routinely used for the detection and identification of chemical substances. Proper sample handling, calibration of instruments, and adherence to standard operating procedures (SOPs) are essential to ensure accuracy and reliability of analytical results [14, 17].

Hands-on experience in handling real forensic samples enhances understanding of practical challenges such as contamination, matrix effects, and instrument sensitivity. Analysts must carefully perform sample preparation steps, including extraction, purification, and concentration, to obtain reliable and reproducible results [13].

In addition, maintaining chain of custody, proper documentation, and strict quality control measures are critical to ensure the legal admissibility of forensic evidence. Routine instrument maintenance, performance checks, and method validation further contribute to consistent analytical performance [46]. Participation in proficiency testing and inter-laboratory comparisons also helps in maintaining analytical standards and laboratory accreditation.

Moreover, exposure to real casework improves problem-solving skills and decision-making abilities, enabling forensic chemists to select appropriate analytical techniques based on sample type and case requirements. The use of laboratory information management systems (LIMS) and digital tools has further enhanced data management, traceability, and reporting efficiency in modern forensic laboratories. Despite these advancements, continuous training and updating of technical knowledge are essential to keep pace with evolving analytical technologies and emerging forensic challenges [9].

Practical laboratory experience highlights several challenges associated with real forensic samples. For example, in a suspected poisoning case, GC–MS or LC–MS/MS may be used to detect pesticides such as chlorpyrifos or organophosphorus compounds in viscera, blood, or gastric lavage samples. The presence of endogenous biological compounds can interfere with analysis, necessitating careful sample extraction and purification prior to instrumental examination [13].

In narcotics investigations, seized powders are often initially screened using color tests and subsequently confirmed by GC–MS or FTIR spectroscopy. For instance, a white powder suspected to be heroin may contain adulterants such as caffeine or paracetamol, requiring chromatographic separation and mass spectral identification to determine the actual drug composition and purity.

In fire debris analysis, GC–MS is used to identify ignitable liquid residues recovered from fire scenes. For example, the detection of characteristic hydrocarbon patterns corresponding to gasoline in burnt carpet or soil samples can assist investigators in determining whether an accelerant was used in an arson incident.

Future Perspectives

Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning (ML) are expected to significantly transform forensic chemistry through automated spectral interpretation, pattern recognition, drug classification, and predictive forensic analysis. These approaches facilitate rapid processing of complex analytical datasets, reducing analysis time while improving analytical accuracy and reliability. Commonly employed AI and ML algorithms in forensic chemistry include principal component analysis (PCA), artificial neural networks (ANNs), support vector machines (SVMs), random forests (RFs), k-nearest neighbors (KNN), and deep learning models. These algorithms are widely applied for pattern recognition, chromatographic and spectral data interpretation, classification of illicit substances, and predictive analysis of forensic datasets. Recent studies have demonstrated the growing application of machine learning in forensic investigations, particularly in evidence classification, toxicological analysis, and forensic data interpretation [47, 48]. However, challenges related to data quality, algorithm transparency, model validation, potential bias, limited availability of standardized forensic databases and legal admissibility remain important considerations for the routine implementation of AI-based systems in forensic laboratories [47, 48].

Portable and Field-Deployable Instruments

The development of portable analytical technologies is enabling real-time forensic investigations at crime scenes. Handheld Raman spectrometers, portable FTIR systems, mobile GC–MS instruments, and miniaturized electrochemical sensors provide rapid screening and preliminary identification of illicit substances, explosives, and trace evidence without requiring laboratory-based analysis. These technologies improve response time and support informed decision-making during field investigations [49].

Nanotechnology-Based Sensors

Nanotechnology offers significant opportunities for enhancing the sensitivity and selectivity of forensic analytical methods. Nanomaterials such as graphene, carbon nanotubes, metal nanoparticles, and quantum dots provide improved signal amplification and lower detection limits for trace-level evidence analysis. Nanomaterial-based sensors have shown considerable promise for the detection of drugs, explosives, toxic chemicals, and biological markers relevant to forensic investigations [50].

High-Resolution Mass Spectrometry

High-resolution mass spectrometry (HRMS) is emerging as a powerful tool in forensic chemistry due to its ability to perform non-target screening, retrospective data analysis, and identification of previously unknown compounds. Its high mass accuracy and resolving power enable ultra-trace detection and comprehensive characterization of complex mixtures, making HRMS particularly valuable for forensic toxicology and the identification of novel psychoactive substances [51].

Green Analytical Chemistry

Environmental sustainability is becoming increasingly important in forensic laboratories. Future developments are expected to emphasize solvent-free extraction techniques, miniaturized analytical platforms, and environmentally friendly sample preparation procedures. Adoption of green analytical chemistry principles can reduce hazardous waste generation, decrease solvent consumption, and improve laboratory sustainability while maintaining analytical performance [52].

Lab-on-a-Chip and Microfluidic Devices

Lab-on-a-chip and microfluidic technologies offer significant advantages for forensic applications by integrating sample preparation, separation, and detection within compact analytical platforms. These systems enable rapid screening, reduced sample consumption, portable forensic testing, and point-of-care toxicological analysis. Continued

advancements in microfluidic devices are expected to improve analytical throughput and accessibility in forensic investigations [53].

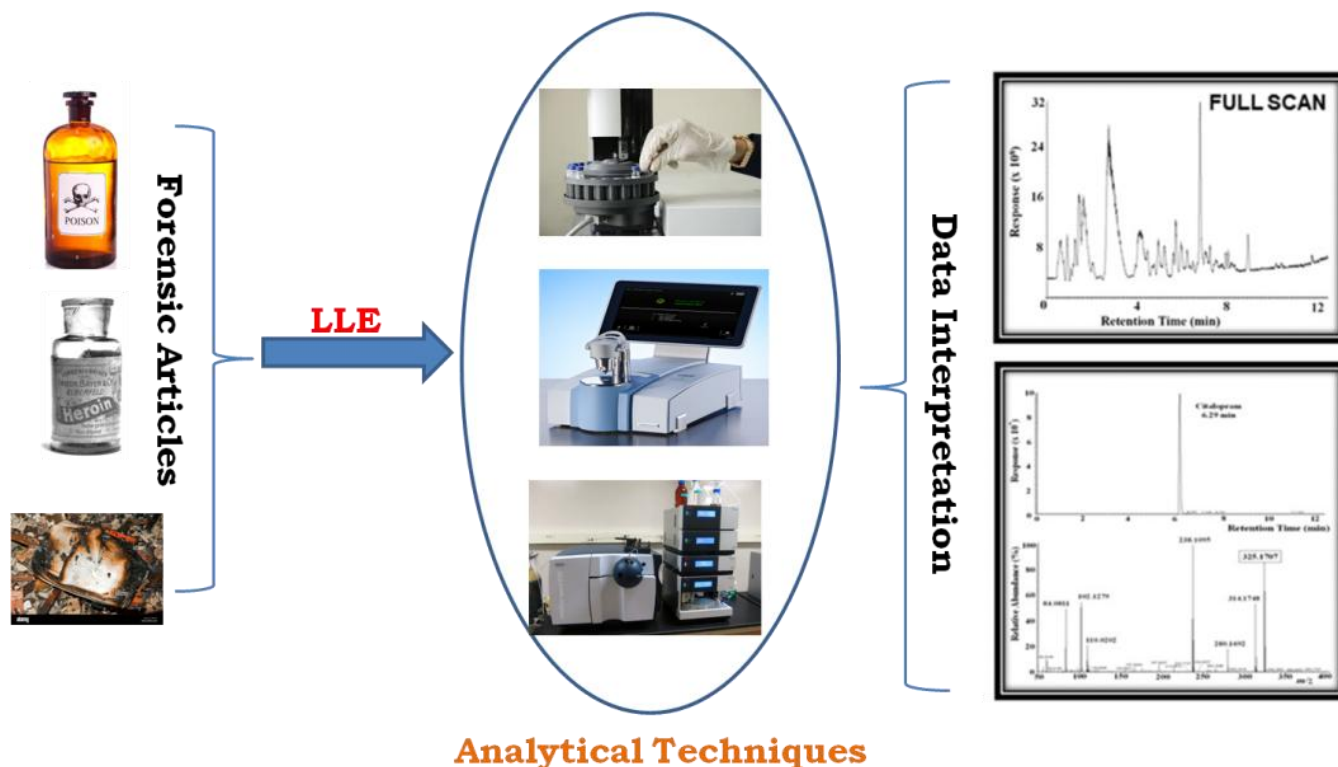


Figure 1 Illustrating emerging technologies in forensic chemistry.

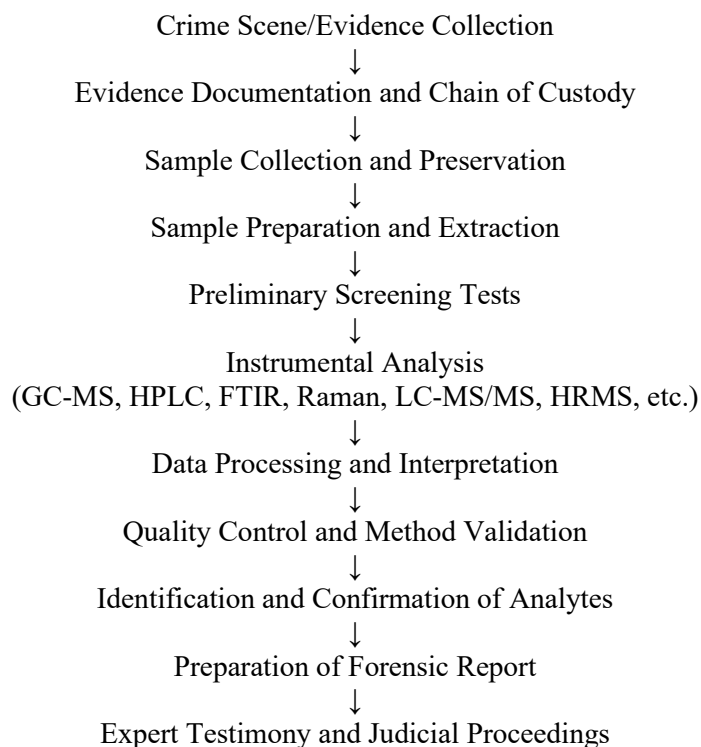


Figure 2 General schematic workflow of forensic chemical analysis

International Standardization and Accreditation

As forensic evidence plays an increasingly critical role in judicial proceedings, greater emphasis must be placed on international standardization and accreditation. Future efforts should focus on harmonized forensic protocols, globally

accessible reference databases, inter-laboratory validation studies, and robust quality assurance systems. These initiatives will improve reproducibility, reliability, and judicial acceptance of forensic analytical results while promoting consistency among forensic laboratories worldwide [54].

Comparative Evaluation of Analytical Techniques in Forensic Chemistry

The revised discussion highlights that GC–MS remains the gold standard for the analysis of volatile and semi-volatile compounds due to its excellent separation efficiency, high reproducibility and extensive spectral libraries that facilitate reliable compound identification [55]. In contrast, HPLC is better suited for the analysis of non-volatile, polar and thermally labile analytes that cannot be readily analyzed by gas chromatographic methods [55]. FTIR and Raman spectroscopy offer rapid, non-destructive analysis with minimal sample preparation requirements, making them valuable for preliminary screening and material identification; however, their sensitivity is generally lower than that of mass spectrometric techniques, particularly for trace-level detection [56].

Table 1 Comparing analytical techniques (GC, HPLC, FTIR, Raman, LC-MS/MS, HRMS)

Technique	Principle	Suitable Samples	Advantages	Limitations	Forensic Applications
GC	Separation of volatile compounds based on boiling point and interaction with stationary phase	Volatile and thermally stable compounds	High separation efficiency, rapid analysis, excellent reproducibility	Not suitable for non-volatile or thermally labile compounds	Drug profiling, arson investigation, toxicology, explosive residue analysis
HPLC	Separation based on differential interaction between analytes and stationary/mobile phases	Non-volatile, polar, and thermally unstable compounds	Wide applicability, high sensitivity, minimal sample preparation	Solvent consumption, longer analysis time	Drug analysis, toxicology, pharmaceutical and poison identification
FTIR	Measurement of molecular vibrational absorption of infrared radiation	Solids, liquids, powders, polymers	Rapid, non-destructive, minimal sample preparation	Limited sensitivity for trace-level analysis	Identification of drugs, fibers, paints, polymers, and unknown materials
Raman Spectroscopy	Detection of inelastic scattering of monochromatic light	Solids, liquids, explosives, narcotics	Non-destructive, little sample preparation, can analyze through packaging	Fluorescence interference in some samples	Drug identification, explosives detection, document examination
LC-MS/MS	Liquid chromatographic separation coupled with tandem mass spectrometric detection	Complex biological and environmental samples	Extremely sensitive and selective, suitable for trace analysis	High instrumentation and maintenance costs	Toxicology, drug screening, pesticide analysis, forensic biology
HRMS	Accurate mass measurement with high resolving power	Complex mixtures, unknown compounds	Precise molecular formula determination, identification of unknowns	Expensive instrumentation and data processing	Emerging drug detection, metabolomics, environmental and forensic investigations

LC–MS/MS provides exceptional sensitivity and selectivity for the quantification and confirmation of analytes in complex biological matrices, making it an indispensable tool in forensic toxicology and drug analysis [55, 56]. Furthermore, HRMS offers superior mass accuracy, high resolving power and non-targeted screening capabilities,

enabling the identification of unknown compounds, metabolites and emerging psychoactive substances that may not be detected using conventional targeted approaches [56]. Nevertheless, the broader implementation of HRMS in routine forensic laboratories remains constrained by the high cost of instrumentation, specialized expertise requirements, and the complexity of data processing and interpretation [56].

Table 2 A timeline of analytical developments

Period	Analytical Development	Significance in Forensic Chemistry
1900–1930	Classical wet chemical analysis	Qualitative identification of poisons, drugs and unknown substances
1930–1950	UV–Visible Spectroscopy	Rapid chemical characterization and quantitative analysis
1950–1960	Infrared (IR) Spectroscopy	Molecular fingerprinting and compound identification
1952	Gas Chromatography (GC)	Separation of volatile compounds with high efficiency
1960–1970	Atomic Absorption Spectroscopy (AAS)	Detection of metals and toxic elements
1970–1980	Gas Chromatography–Mass Spectrometry (GC–MS)	Highly reliable identification of drugs, explosives and toxins
1980–1990	High-Performance Liquid Chromatography (HPLC)	Analysis of non-volatile and thermally unstable compounds
1990–2000	Fourier Transform Infrared (FTIR) and Raman Spectroscopy	Rapid, non-destructive forensic examinations
2000–2010	Liquid Chromatography–Tandem Mass Spectrometry (LC–MS/MS)	Ultra-trace detection in toxicology and forensic biology
2010–2020	High-Resolution Mass Spectrometry (HRMS)	Accurate mass determination and non-targeted screening
2020–Present	Ambient Ionization MS, Portable Spectroscopy, AI-Assisted Analysis, Microfluidics	Real-time, field-based, and data-driven forensic investigations

Conclusion

Forensic chemistry plays a pivotal role in modern criminal investigations by providing reliable scientific analysis of chemical evidence. The integration of advanced analytical techniques such as chromatography, spectroscopy, and mass spectrometry has significantly enhanced the sensitivity, accuracy, and speed of forensic examinations. These techniques enable precise identification and quantification of a wide range of substances, including drugs, toxins, explosives, and environmental contaminants, even at trace levels.

Recent advancements, including hyphenated techniques, high-resolution instrumentation, automation, and digital data processing, have further strengthened the efficiency and reliability of forensic analyses. Additionally, the incorporation of emerging technologies such as artificial intelligence and portable analytical devices has expanded the scope of forensic investigations, enabling rapid on-site analysis and improved decision-making.

Despite these developments, challenges such as sample contamination, high operational costs, the need for skilled personnel, and stringent legal requirements continue to impact forensic practices. Addressing these limitations through standardization, quality assurance, and continuous training is essential for ensuring the credibility and admissibility of forensic evidence.

Overall, ongoing research and technological innovation are expected to further advance forensic chemistry, making analytical techniques more sensitive, cost-effective, and environmentally sustainable. These improvements will continue to support the justice system by providing accurate, reliable, and timely forensic evidence.

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References

- [1] Saferstein R. *Criminalistics: An Introduction to Forensic Science*; Pearson: 2015.
- [2] Houck M.M.; Siegel J.A. *Fundamentals of Forensic Science*; Academic Press: 2010.

- [3] Skoog D.A.; Holler F.J.; Crouch S.R. Principles of Instrumental Analysis; Cengage Learning: 2014.
- [4] Askar A.M.; et al. Rapid GC-MS method for screening seized drugs in forensic investigations: optimization and validation. *Front. Chem.* 2025, 13, 1559279.
- [5] Zhang Y.; et al. Screening of forensic drugs using high-resolution mass spectrometry. *Chem. Res. Toxicol.* 2024, 37(4), 571–579.
- [6] Mishra A.K.; et al. Recent advancements in liquid chromatographic techniques. *Crit. Rev. Anal. Chem.* 2024, 54(8), 2900–2914.
- [7] Wilson W.B.; et al. Analytical methods for cannabinoid determination in forensic laboratories. *Forensic Chem.* 2024.
- [8] Smith J.; et al. New applications of GC and GC-MS for novel sample matrices in forensic sciences. *J. Forensic Sci.* 2023, 11(10), 527.
- [9] Bell S. *Forensic Chem.*; Pearson Education: 2020.
- [10] Vandenabeele P. *Practical Raman Spectroscopy: An Introduction*; Wiley: 2013.
- [11] Crocombe R.A. *Portable spectroscopy*. *Appl. Spectrosc.* 2018, 72(12), 1701–1751.
- [12] Sharma S.K.; et al. Handheld spectroscopic instruments in forensic science. *TrAC Trends Anal. Chem.* 2021, 134, 116127.
- [13] Peters F.T.; et al. Analytical challenges in forensic toxicology. *Anal. Bioanal. Chem.* 2020, 412, 3549–3563.
- [14] UNODC. *Guidance for the Validation of Analytical Methodology*; United Nations: 2021.
- [15] Eurachem. *The Fitness for Purpose of Analytical Methods*; 2020.
- [16] Armenta S.; Garrigues S.; de la Guardia, M. Green analytical chemistry in forensic science. *TrAC Trends Anal. Chem.* 2019, 116, 248–253.
- [17] Puch-Solis R.; et al. Artificial intelligence in forensic science. *Forensic Sci. Int.* 2021, 318, 110610.
- [18] Sahu R.; Yadav, S. Machine learning approaches in forensic data analysis. *J. Forensic Sci.* 2022, 67(3), 1025–1035.
- [19] Grabenauer M.; et al. High-resolution mass spectrometry in forensic drug analysis. *J. Am. Soc. Mass Spectrom.* 2020, 31(5), 816–829.
- [20] Meyer M.R.; Maurer, H.H. Detection of new psychoactive substances using HRMS. *Anal. Bioanal. Chem.* 2020, 412, 3807–3822.
- [21] Krauss M.; et al. HRMS for environmental and forensic analysis. *TrAC Trends Anal. Chem.* 2021, 138, 116220.
- [22] Ifa D.R.; Eberlin, L.S. Ambient ionization mass spectrometry for forensic applications. *Clin. Chem.* 2016, 62(1), 111–123.
- [23] Hu B.; et al. Advances in microextraction techniques. *TrAC Trends Anal. Chem.* 2021, 143, 116367.
- [24] Kataoka H. Developments in microextraction methods. *J. Chromatogr. A* 2020, 1633, 461615.
- [25] Roux C.; et al. Digital transformation in forensic science. *Forensic Sci. Int.* 2021, 318, 110571.
- [26] Baechler S.; et al. Automation in forensic laboratories. *Forensic Sci. Int.* 2020, 307, 110120.
- [27] Poole C.F. *Gas Chromatography*; Elsevier: 2020.
- [28] Sparkman O.D.; Penton, Z.; Kitson F.G. *GC-MS: A Practical Guide*; Academic Press: 2019.
- [29] Dong M.W. *Modern HPLC for Practicing Scientists*; Wiley: 2019.
- [30] Swartz M.E. UHPLC in pharmaceutical and forensic analysis. *LCGC North Am.* 2020, 38(6), 280–286.
- [31] Niessen W.M.A. *Liquid Chromatography–Mass Spectrometry*; CRC Press: 2017.
- [32] Maurer H.H. LC–MS/MS in forensic toxicology. *Anal. Bioanal. Chem.* 2021, 413, 603–618.
- [33] Thevis M.; et al. Mass spectrometry in doping control. *Annu. Rev. Anal. Chem.* 2018, 11, 483–504.
- [34] Krueve A.; et al. Matrix effects in mass spectrometry. *Anal. Chem.* 2019, 91(1), 1–14.
- [35] Rouessac F.; Rouessac, A. *Chemical Analysis: Modern Instrumentation*; Wiley: 2019.
- [36] Christian G.D. *Anal., Chem.*; Wiley: 2014.
- [37] Stuart B. *Infrared Spectroscopy*; Wiley: 2019.
- [38] Smith B.C. *FTIR Spectroscopy Fundamentals*; CRC Press: 2011.
- [39] Hoffmann E.D.; Stroobant V. *Mass Spectrometry: Principles and Applications*; Wiley: 2019.
- [40] de Hoffmann E.; Stroobant, V. *Mass Spectrometry Fundamentals*; 2007.
- [41] Levine B. *Principles of Forensic Toxicology*; Springer: 2019.
- [42] Yinon J. *Forensic Applications of Mass Spectrometry*; CRC Press: 2016.
- [43] Everstine K.; et al. Food fraud detection. *J. Food Prot.* 2019, 82(1), 94–101.
- [44] Murphy B.L.; Morrison, R.D. *Environmental Forensics*; Academic Press: 2014.
- [45] Harris D.C. *Quantitative Chemical Analysis*; W.H. Freeman: 2020.
- [46] ISO/IEC 17025. *General Requirements for Testing and Calibration Laboratories*; 2017.
- [47] Barash M.; McNevin D.; Fedorenko V.; Giverts P. Machine learning applications in forensic DNA profiling: A critical review. *Forensic Sci. Int. Genet.* 2024, 69, 102994.

- [48] Hachem M.; Mizouni R.; Alawadhi I.M.; Altamimi M.J. Digital forensic intelligence for illicit drug analysis in forensic investigations. *iScience* 2023, 26(10), 108023.
- [49] Bell S.; Crocombe R.A. Portable spectroscopic technologies for forensic field investigations. *Anal. Methods* 2022, 14, 4201–4215.
- [50] Wang J.; Merkoçi A. Nanomaterial-based sensing platforms for forensic analysis. *Biosens. Bioelectron.* 2023, 219, 114798.
- [51] Hernández F.; Ibáñez M.; Portolés T.; Cervera M.I. High-resolution mass spectrometry in forensic and toxicological analysis: Recent advances. *Anal. Bioanal. Chem.* 2023, 415, 2745–2763.
- [52] Płotka-Wasyłka J.; Namieśnik J. Green analytical chemistry in forensic science laboratories. *TrAC Trends Anal. Chem.* 2022, 149, 116542.
- [53] Li X.; Ballerini D.R.; Shen W. Lab-on-a-chip devices for rapid forensic analysis. *Lab Chip* 2022, 22, 3200–3218.
- [54] Morgan R.M.; Meakin G.E.; French J.C. Strengthening quality assurance and standardization in forensic science. *Forensic Sci. Int. Synergy* 2024, 7, 100456.
- [55] H.H. Maurer, Current role of liquid chromatography–mass spectrometry in forensic, clinical, and environmental analysis, *Anal. Bioanal. Chem.*, 2007, 388, 1315–1325.
- [56] T.J. Causon, S. Hann, Theoretical evaluation of peak capacity improvements by use of liquid chromatography coupled to high-resolution mass spectrometry, *J. Chromatogr. A*, 2015, 1421, 47–59.

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